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Environmental Studies No. 1

Impact of Seismic Activity
on Muskrat Populations on
the Mackenzie Delta





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SUMMARY

Research was initiated in March 1976 to resolve the question of whether or not seismic exploration is injurious to muskrat populations. The Study Area is located at 68°30' N latitude and 134°30' W longitude, near the centre of the Mackenzie Delta.

Three main types of investigations were undertaken, namely: (1) direct effects experiments (injury and stress caused by explosions), (2) population studies (changes in numbers and reproduction), and (3) activity studies (pushup abandonment and behavioral alteration).

Recording of peak pressures in conjunction with direct effects experiments were complicated by recording difficulties, but pressure changes that were recorded following detonation of 11 kg and 22 kg charges were well below lethal pressures reported in the literature. After examination for signs of injury or stress, muskrats were exposed to experimental blasts in simulated bank-burrows, pushups and in water at specified distances from the shot points. Results of post-treatment pathological and histological examinations indicated that blast effects were minimal, consisting mainly of minor middle ear and lung damage. Most animals showing signs of blast effects had been situated in bank-burrows 6 m from shot holes or were submerged in water 15 m from shot holes.

Adrenal gland weights and histological sections of glands were analyzed to provide information regarding immediate and long-term blast initiated stress. No correlations were evident for any of the indices used. It must be concluded that either animals demonstrated no long or short-term stress, or that the methods used were not appropriate for measuring these factors.

The results of livetrapping and steel-trapping procedures to estimate pre-seismic and post-seismic population levels were analyzed using the Schnabel estimator. No significant changes in population level were demonstrated for either experimental or control lakes.

Reproductive performance among females collected from experimental and control lakes in June was compared. No significant differences existed between the two groups in terms of: (1) proportion of females gravid, (2) mean numbers of embryos, or (3) incidence of embryo resorption. Examination of reproductive tracts yielded an average expected litter size of 8.06.

No significant decrease in the number of active pushups were found following seismic exploration in either experimental or control lakes. However, significant differences were found in the proportion of active pushups at various distances from seismic lines that crossed lakes. The proportion of active pushups was much larger at distances greater than 180 m from lines ($P < 0.01$)

Pushup utilization was monitored using electrically recording probe switches. The data indicate that while monitored pushups continued to be visited by muskrats after the blast, there was a 53% decrease in the number of visits per 24-hour period.

Although small numbers of pushups were inadvertently destroyed by heavy equipment crossing lakes, other activities associated with seismic exploration did not appear to threaten the welfare of muskrats. Nothing is known, however, of the effect of noise on the behavior of muskrats exposed to blasting.

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1.0 INTRODUCTION

This report presents results from the first year of investigations on the effects of seismic activity on muskrat populations (*Ondatra zibethicus spatulatus*) in the Mackenzie Delta. Trappers in the region have expressed concern from time to time, that activities associated with seismic exploration were injurious to muskrats and that population levels were affected. The Arctic Land Use Research Program (ALUR), in response to these concerns, commissioned an investigation to resolve these questions.

The overall objective of this study was therefore to ascertain the effects of seismic activity on muskrat populations in the Mackenzie Delta. More specifically, our objectives were to:

- (a) determine whether seismic explosions injure or kill muskrats directly,
- (b) determine whether seismic blasting or related activity causes abandonment or destruction of pushups,
- (c) determine the effect of seismic explosions on the normal activity of muskrats,
- (d) determine whether seismic activity contributes to altered or reduced reproduction.

The study was initiated in mid-winter, 1976. A preliminary meeting of all cooperating agencies and individuals was scheduled for February, at which time a format for the study and a time frame were agreed upon. The first phase of a program of field investigation began in March and continued until 3 May. The second phase included the period 4 June to 25 June. Necropsies and supplementary laboratory work were conducted throughout the study.

2.0 NATURE OF SEISMIC OPERATIONS

2.1 Theory of Seismic Exploration

Seismic exploration, based on the principles of seismology, is a method by which geophysicists locate oil and/or gas bearing geological formations. A controlled series of explosions on the ground surface provides the energy for the creation of "elastic" waves, which travel downward in all directions according to physical laws similar to those of optical theory. These waves are reflected and refracted

at interfaces of rock layers at depth and return to the surface of the earth where they are recorded. A series of geophones measure the velocity of the waves returning to the surface and transform them into electrical energy which is then recorded on a seismograph. The interpretation of the seismographic recording provides a section of geological layers beneath the surface.

The most common type of seismic shooting employed by exploration companies on the Mackenzie Delta is the single line method, where recording is received from a single line of shot holes, fired singly at regular intervals. The depth, interval, and the amount of explosive loaded varies depending on the geological conditions to be explored and the approach of the exploration company involved.

Two kinds of elastic waves are generated by a seismic explosion and transmitted through solid material. Longitudinal waves, known as primary (P) or compressional waves, are faster travelling than the second kind known as transverse or shear (S) waves. The frequency of P and S seismic waves range between 15 c/sec and 100 c/sec (Paranis 1966). Combinations of P and S waves may also be created by reflection and refraction of P and S waves at interfaces of different media. The velocity of P and S waves vary depending upon the density and other characteristics of the medium but usually remain constant to such an extent that geological strata can be interpreted from them. Fluids however, such as air and water, do not possess shear strength and therefore cannot transmit S waves.

The propagation of elastic waves and the resultant forces are the function of a number of interacting phenomena, the most important of which are amplitude (peak pressure), shape of the compressional wave and rarefaction.

- (a) In a homogenous medium, the peak pressure undergoes an exponential decay with distance, that is a function of the type of charge and its weight. At a given distance from a blast, peak pressures increase with larger charges but the increase is only in proportion to the one-third power of the charge. For example, a five kilogram charge produces one-third the pressure of a 125 kilogram charge. The rate at which the peak pressure decreased with distance varies with the medium. Hubbs and Rechnitzer (1952) reported that in open water the peak pressure from a dynamite explosion decayed inversely as the first power of the distance. They also showed that when explosives were placed beneath the bottom, the energy decay was much greater; using a five pound charge of dynamite, they found that the pressure decreased inversely as the 2.6 power of the distance. It is also known that high frequency waves attenuate more rapidly than do low frequency waves.

- (b) A compressional wave is created as a result of a large and rapid evolution of energy. The shape of the compressional wave is determined by the type of explosive used. High explosives such as dynamite or 60% Geogel explode almost instantaneously, producing a compressional wave with a very steep shock front. Such waves, when propagating through water cause very rapid pressure changes. In contrast, low explosives such as black powder burn more slowly and do not produce a shock wave with an abrupt front.
- (c) The acoustic impedance of a medium is expressed by the function $w = p \times V$ where w is the acoustic impedance, p is the density of the medium and V is the velocity of the propagating wave. When the initial positive compression wave from an energy source is reflected from the surface of a medium with a smaller acoustic impedance, as from the water-air interface, the reflected wave assumes the negative sign through change of phase. The negative pressure pulse is referred to as rarefaction. Due to this phenomenon, greater pressure changes can be encountered at the surface of the water; and for any point below that surface, the difference in wave amplitude and time of arrival must be taken into account. Cole (1948) reported that natural waters cannot support negative pressures greater than one atmosphere due to the dissipation of energy through cavitation. The downward propagation of the negative pressure wave through the water becomes rapidly attenuated with distance due to the increasing hydrostatic pressure.

The nature of the lake bottom may also be instrumental in affecting pressure waves in the water. A lake bottom that provides a rigid boundary can act as a reflector of pressure. The degree to which the resulting pressure increases and its duration are dependent upon the nature of the bottom material. Rasmussen (1967, cited by Falk and Lawrence 1973) found during experiments on the effects of underwater explosions on marine life, that the lethal pressure is intensified when large amounts of energy are reflected upward from a charge detonated above a solid stratum.

When seismic blasts occur near ice covered water, additional pressures can result from ice flexure waves which may cause undulation of the ice cover. This can result in alternating conditions of increased pressure during compression followed by negative pressure changes during rarefaction.

Some recent data involving water pressures resulting from seismic blasting experiments have been reported by oil companies during offshore seismic operations on the Mackenzie Delta. The results of these experiments indicate a great variance in the recorded water pressures. Experiments by Gulf Oil Canada Ltd. revealed a peak water

pressure of 3 psi when a 10 pound, 60% geogel charge was detonated in a shot hole 75 feet below lake bottom where water depth and ice thickness were six feet and four feet respectively. However, in the Kugmallit Bay area in similar water depth and ice thickness, Sun Oil Company's experiment showed that a five pound explosive detonated in a shot hole 60 feet below ice surface yielded a peak pressure of 40 psi in a radius of approximately 225 feet from the shot hole. The investigators suggest that factors such as ice thickness, water depth, medium surrounding the explosive charge and type of energy source used, have an effect on the peak pressure created (Fisheries and Marine Service 1975).

2.2 Imperial Oil Limited Program

The seismic program conducted by Imperial Oil was initiated on 31 March 1976 and completed on 10 April 1976. Seismic operations on the Delta are usually completed by the third week in April due to deterioration of the ice roads on the river channels.

A total of approximately 53 km of seismic line were shot of which all except 13 km were along existing lines. The newly constructed lines, like the existing ones, were approximately 6 m wide and oriented on the basis of geodetic datum. The lines were prepared by "walking" the crawler tractors along the designated line several times providing a packed snow surface. Essentially all vegetation along the line was tramped down into the packed snow surface. Where seismic lines crossed steep shorelines of lakes and stream channels, snow ramps were constructed. The ramps in the channels were removed after the completion of the seismic operation. Shot holes, 10 cm in diameter, were drilled to a depth of 18 m at 122 m intervals. Regulations disallow seismic shooting on the lakes and within 12 m of their shorelines. The shot holes were loaded with 6.8 kg of 60% Geogel (a point high explosive). Mark-Land geophones were positioned on the packed snow surface at 30.5 m intervals to record reflected energy. The seismic recording units were capable of receiving a frequency range of 5 - 100 c/sec.

3.0 CURRENT KNOWLEDGE OF SEISMIC EFFECTS ON WILDLIFE

Much information has been gathered in recent years regarding the effects of underwater explosions on fish and other marine life (Falk and Lawrence 1973, Paterson and Turner 1968, and Kearns and Boyd 1965). The findings of these and other researchers indicate that blast effects are most severe in species which possess swim bladders. Injuries to fish, resulting from underwater explosions ranging from 0.6 kg to 544 kg of high explosives, include rupture or hemorrhage of the swim bladder, abdominal vein, spleen, liver, heart and ripe gonads. The hypothesis is presented that high velocity underwater explosions

produce rapid changes in hydrostatic pressure resulting in disruption of the viscera. Low velocity explosions produce less severe effects.

Fitch and Young (1948, cited by Falk and Lawrence 1973) noted that certain species of fish having thick-walled swim bladders and a cylindrical body, were more shock pressure resistant than laterally compressed, thin-walled swim bladder species. Experiments conducted by Hubbs and Rechnitzer (1952) showed that fish were often killed by charges as small as 0.6 kg and that a 2.3 kg (5.0 lb) charge buried 19.8 m (65 ft) below the ocean bottom resulted in fatality of experimental fish placed both at the bottom and near the surface of the water. They also reported that fish are very sensitive to negative pressures (less than one atmosphere) due to rarefaction near the surface of the water. In addition to hemorrhaging, burst air bladders and disruption of the viscera, negative pressure may cause injury or death through the formation of gas bubbles in body fluids. The sudden liberation of dissolved gas may rupture the walls of unprotected blood vessels. They concluded that lethal threshold peak pressures from dynamite varied from 40 to 70 psi.

Rasmussen (1967, cited by Falk and Lawrence 1973) showed that the effects of pressure changes on fish depend largely on age of the individuals effected. He found that newly hatched herring and salmon fry were resistant to pressure changes but that at three to six months of age the same species were killed by blasts exceeding 2.7 psi. The resistance of newly hatched fry was due to their yet undeveloped swim bladders.

Much less information is available on the tolerances of mammals to blast pressure changes. Rausch (1973) reported on the effects of the Cannikin test on some marine animals off the coast of Amchitka Island. The finding revealed that peak pressures ranging from 100-300 psi were lethal to sea otters and harbour seals. Post mortems indicated that thoracic organs, central nervous system, and the middle ear were most severely affected. It was postulated that the disruptive results were caused by a relatively slow rising pressure pulse followed by a negative pressure phase, culminating in cavitation, and a subsequent rise to the pre-existing ambient pressure level.

In a preliminary assessment of the effect of seismic operations on the Mackenzie Delta, Martin (1973) was unable to link seismic activity with changes in muskrat populations.

4.0 STATUS OF MUSKRATS IN THE MACKENZIE DELTA

The muskrat is a semi-aquatic rodent which occurs throughout North America where suitable aquatic habitats are found. Adaptive pressures vary greatly over this vast range, resulting in subspecies or populations that differ morphologically and behaviorally depending on local stresses and habitat characteristics. Local variables of importance to the northwestern muskrat (*Ondatra zibethicus spatulatus*) of arctic and sub-arctic Canada and Alaska include temperature and seasonality, habitat type and the presence of a spring flood.

Most animals occupying arctic environments are morphologically adapted to the severe climatic conditions through a tendency to large size hence less surface area per unit body weight (Bergmann's rule). The northwestern muskrat however, is a small race, and Mackenzie Delta representatives are the smallest examples of this race (Stevens 1955). The hypothesis put forward to account for this seeming inconsistency is that by occupying less favorable habitat this subspecies, on the Mackenzie Delta in particular, is not achieving its full potential for growth. The unfavorability of the arctic habitat is primarily caused by limited availability and poor quality of food supplies.

Musk rats have long been considered versatile feeders, utilizing a diversity of food sources. When food is abundant, marked preferences for certain types and parts of plants are common, but when winter ice reduces the availability of most plants, animals are able to utilize that which is available even if a low priority food. In the Delta, pronounced seasonal differences in diet occur with emergent species selected in summer whereas in winter, when ice conditions render these unavailable, submergents are eaten instead.

Although muskrats in more temperate regions are able to occupy houses, made of available vegetation, as well as burrow systems in steep banks, Delta muskrats are restricted to the latter form of residence by a lack of emergent vegetation and great ice thicknesses. Young are born in these 'bank burrows', and in winter, animals swim out from them, extending their foraging range by means of 'pushups', or hollow feeding stations constructed on the ice surface and accessible only through a hole in the ice ('plunge hole'). Large numbers of pushups are constructed in the fall, although many are abandoned later in the winter as the plunge-holes become frozen.

Relatively deep lakes are required for winter occupancy by muskrats, although suitable summer habitat need only provide banks for burrows, a food source, and enough water to cover burrow entrances. Since ice thicknesses are in the range of 1 m, and open water beyond this depth is required to provide access to food supplies, lakes less than 1 m deep are considered too shallow to support wintering populations.

With the onset of break-up and the start of the breeding season, widespread dispersal takes place as young adults abandon winter habitat in search of breeding territories of their own. At this time usable habitat is extensive and mated pairs, together with their young, occupy virtually all water bodies. As winter approaches though, and shallow water bodies are threatened by drought and freeze out, movement again occurs back to the deeper wintering lakes. Since these lakes are not able to support such large numbers, extensive mortality takes place during the first few weeks of winter. This period of mortality may account for as much as 50% of the year's increment of juveniles (Hawley and Hawley 1975).

Behavioral adjustments to the severe arctic environment such as those associated with use of bank burrows, pushup building, seasonal dietary changes and movements, are important to the survival of the species at these latitudes. Of equal importance are genetically controlled adaptations such as those associated with reproduction. The ice-free period, in the Delta, is about four months long, during which time mating and breeding must take place, and young animals must be reared to a stage of maturity sufficient for over winter survival.

Males appear to enter breeding condition earlier and more gradually than females. On the Mackenzie Delta, Stevens (1955) noted viable spermatozoa as early as March 23, with most males in full breeding condition by April. Females however, do not show signs of entering breeding condition until mid-April, and are not usually ready to begin breeding until May. In both males and females, adults approach breeding condition more rapidly than yearlings. The onset of breeding activity is correlated with spring break-up and flooding, which usually occur in early June. Following a four week gestation period, litters begin appearing in mid-June, although most young are not born until early July (Stevens 1955). Errington (1962) reviewed the findings of many workers in the United States who found that females in the central and southern states often produce four litters per year and five litters were occasionally documented. Even as far north as the Peace-Athabasca Delta, Westworth (1974) found that three litters per year were produced by 44% of the females in the population studied. Stevens (1955) however, found one litter per year to be the norm, and two to be moderately common in the Aklavik area.

The ecological disadvantage of producing a small number of litters is partially offset by an increased tendency toward large litter sizes in northern latitudes. In the southern states, average litter size is about 4.0 (Errington 1962), whereas in the Mackenzie Delta Stevens recorded an average of 8.3 young, and Hawley and Hawley (1975) observed averages between 7.25 (in 1963) and 9.0 (in 1970) young per litter.

Whereas the climatically induced rigors of the northern environment constitute a major controlling influence, other decimating factors tend to be of less significance compared to more southerly

regions. For example, the lower population densities on the Delta appear to be associated with a reduced tendency toward intraspecific intolerance. Fighting, although common during the breeding season, is of short duration and thereafter only of local occurrence (Stevens 1955). In addition, predation (other than fur trapping) is very low, and accounts for an insignificant proportion of total mortality. Disease and parasitism are also generally low. This may be the result, in part, of the cleansing action of spring floods (Stevens 1955) and of low population densities that reduce the spread of disease.

5.0 DESCRIPTION OF THE STUDY AREA

Investigations were centred on 14 lakes scattered in the vicinity of the confluence of Napoiak and Taylor Channels at 68°30' north latitude and 134°30' west longitude (Figure 1). The Study Area was in the traditional trapping areas of Isaac Simons and Big Jim Rogers. The longest distance between any two lakes was 11.12 km. Orientation and placement of seismic lines relative to study lakes is illustrated in Figure 2. The Study Area is located in the lower half of the Mackenzie Delta, within the Arctic Coastal Plain physiographic region (Douglas 1969). Local relief is minimal, consisting primarily of channel levees, lakeshores and intermittent channel beds. Soils are almost all depositional in origin, ranging from the coarse gravels along channel margins to the fine silts and clays borne by flood waters. Organic soils such as those associated with *Sphagnum* bogs may also be present.

Terrestrial vegetation resembles that described by MacKay (1963) for the Mackenzie Delta Spruce-Willow-Alder-Poplar community. Channel banks are covered with sedges (*Carex* spp.), grasses, horsetail (*Equisetum* spp.) and low growing willows (*Salix* spp.). Dense thickets of alder (*Alnus crispa*) and willow occupy the levee tops. White spruce (*Picea glauca*) is common in the area (Photo 1) and where found, is accompanied by a dense understory of willows, alders and grasses. Lakes were surrounded by dense thickets of willow and alder, with understory grasses, sedges and horsetails (Photo 2). Shallow, marshy areas supporting emergents were not common. An analysis of pushup composition was conducted to ascertain qualitative differences in aquatic vegetation between study lakes. Although variability between lakes was evident, it did not seem to correlate with lake size or depth, or the occurrence of a spring flood (Table 1). *Potamogeton* was abundant in all lakes and nearly all samples. Members of the Gramineae and Characeae were also very common, as was *Myriophyllum*.

Although shape and areal size of lakes studied varies considerably, other characteristics appear fairly similar. Only two study lakes underwent substantial flooding; the remainder were increased only by local runoff. Lakes have typically steep banks, the result of thermokarst action around their perimeters; bank slumping was a consistent phenomenon. Ice thickness did not vary greatly between lakes, but water depth below the ice did show considerable differences (Table 2). The minor differences in snow depths between lakes seemed not to have an important effect on ice thickness.

Meteorological information indicates that the 1976 temperature regime was comparable to previous years (Appendix I). Data show that spring precipitation is highly variable, but there is no indication that unusual weather conditions contributed to the results of this study.

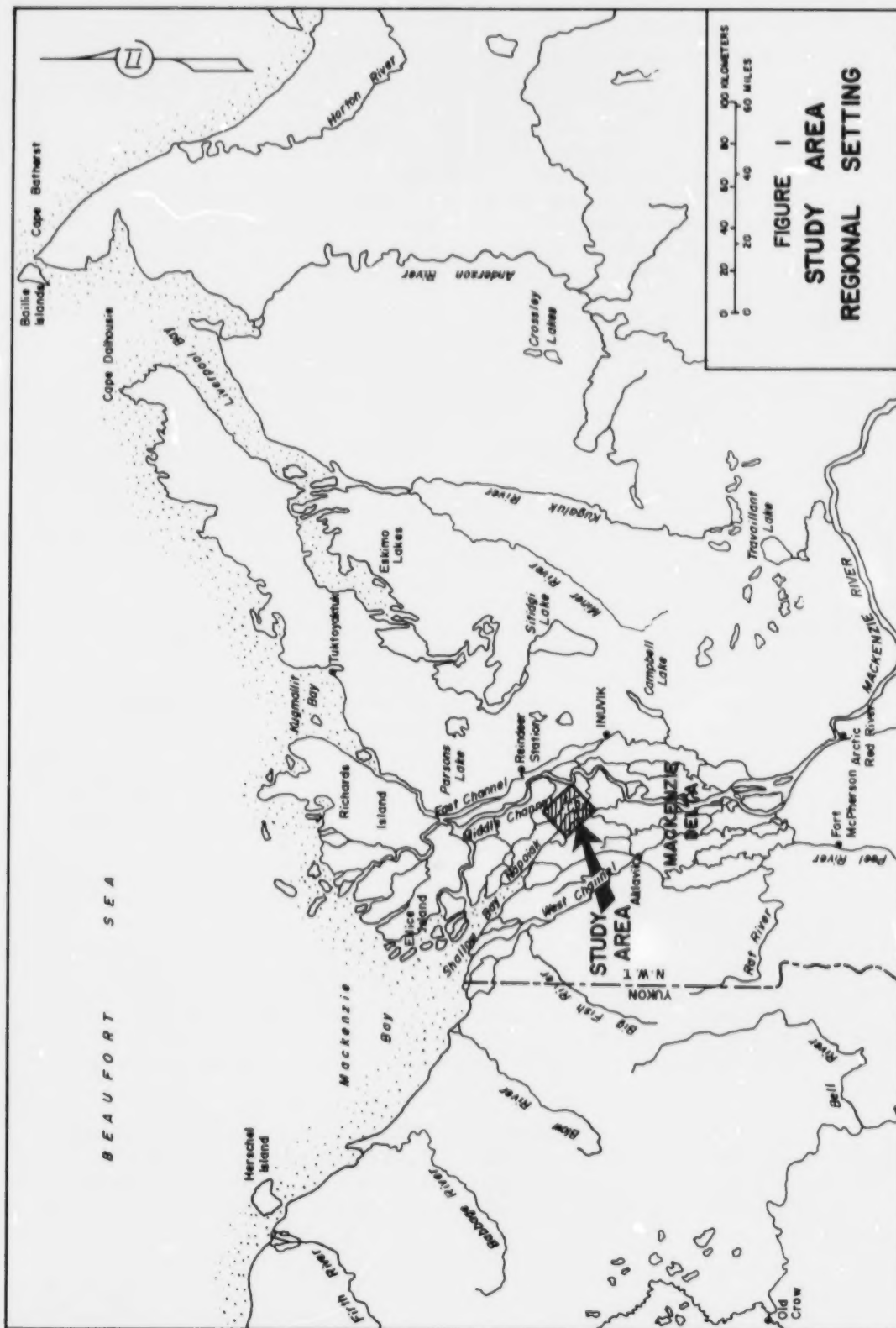
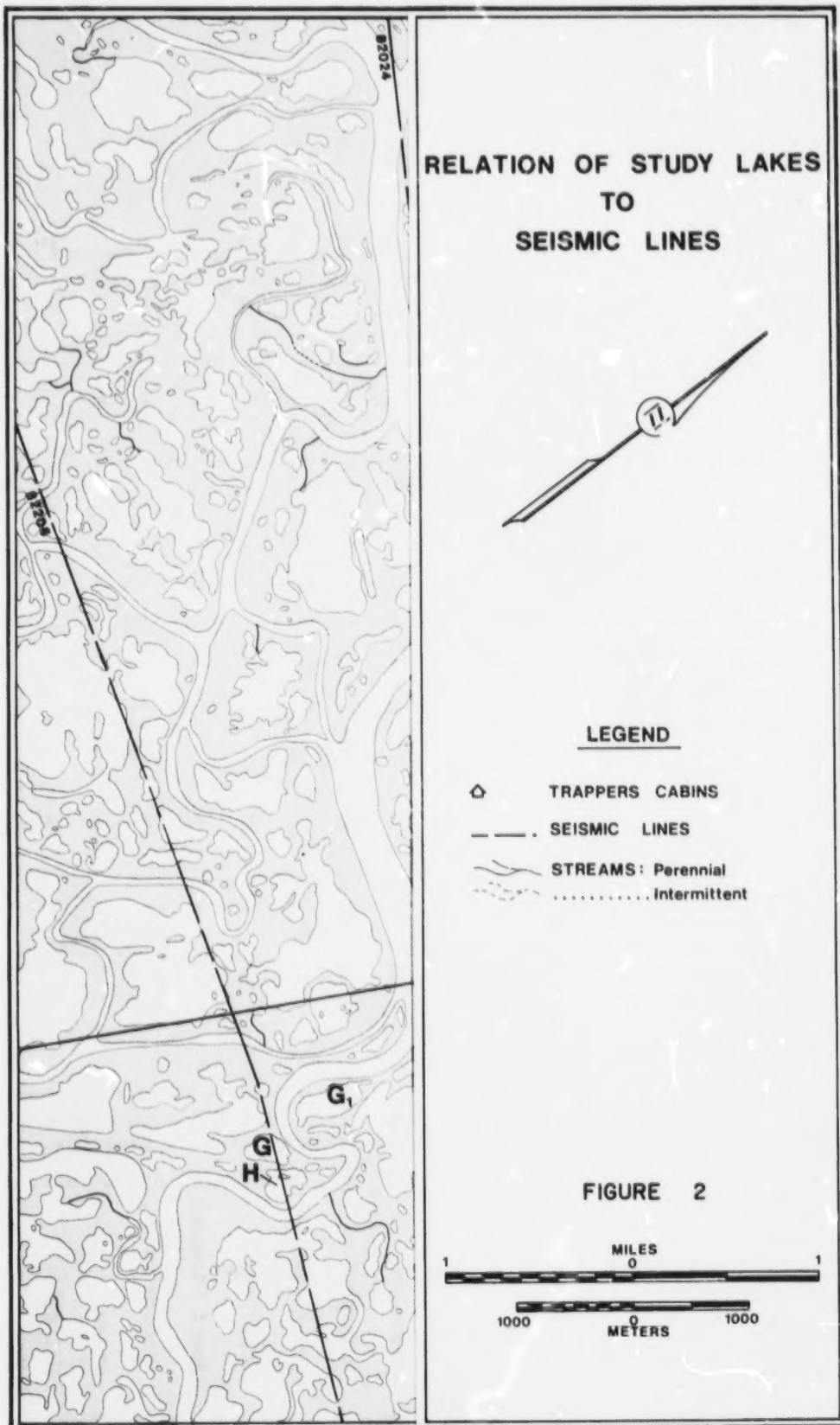


FIGURE 1
STUDY AREA
REGIONAL SETTING



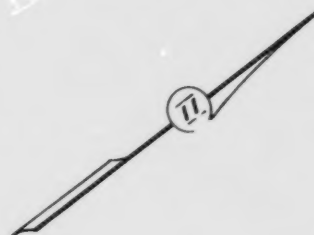
Red River Mackenzie

Pel





RELATION OF STUDY LAKES TO SEISMIC LINES



LEGEND

- ⊠ TRAPPERS CABINS
- SEISMIC LINES
- STREAMS: Perennial
- Intermittent

FIGURE 2

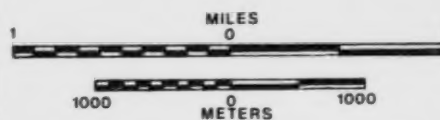


Table 1. Composition of pushup samples from Study Area lakes.

Species	% Occurrence										
	B	B ₁	D	D ₁	E	E ₁ *	F	F ₁ *	G	G ₁	Mean
<i>Potamogeton richardsonii</i>	70	95	90	95	80	92	100	100	100	95	92
<i>Potamogeton</i> spp.	45	35	-	45	80	46	60	65	25	55	46
Characeae	90	80	75	100	100	100	45	88	25	75	78
<i>Equisetum fluviatile</i>	-	10	15	-	-	8	-	18	10	-	6
Gramineae	55	30	50	70	60	100	95	88	45	85	68
<i>Myriophyllum exallescens</i>	25	20	50	50	65	38	20	47	75	45	44
<i>Ceratophyllum</i> sp.	15	15	10	55	55	-	-	12	-	5	17
<i>Carex</i> sp.	15	-	20	-	-	-	-	-	-	-	4
Musci (Mosses)	-	-	5	-	-	62	-	6	-	-	7
<i>Sparganium</i> sp.	-	-	10	-	-	-	-	-	-	-	1
<i>Picea</i>	5	-	-	-	-	-	-	6	-	-	1
<i>Salix</i>	5	5	-	-	5	8	-	-	-	5	3
Misc.	-	20	-	-	15	-	20	-	-	-	6

*N = 20 for all lakes except Lake E₁ (N = 13) and Lake F₁ (N = 17).

Table 2. Summary of water depth, snow depth and ice thickness data for Study Area lakes, April 1976.*

Lake	Sample	Mean Ice Thickness (cm)	Mean Water Depth** (cm)	Mean Snow Depth (cm)
B	5	135.0	70.0	12.5
B ₁	ND	ND	ND	ND
C	ND	ND	ND	ND
C ₁	ND	ND	ND	ND
D	5	108.3	38.4	18.1
D ₁	5	107.5	65.0	15.6
E	7	117.1	120.0	22.8
E ₁	5	87.5	96.3	ND
F	5	106.7	46.7	17.5
F ₁	5	85.0	80.0	23.3
G	6	90.2	28.8	38.7
G ₁	5	110.0	50.8	15.4
$\bar{X}$		105.3	66.2	18.3

* Measurements were taken in the vicinity of known pushup concentrations, and more than 35 m from shore

** Mean water depth below ice

6.0 METHODS

6.1 Direct Effects

6.1.1 *Effects of Peak Pressures*

Two experiments were conducted to ascertain direct effects of seismic blasting near the shoreline of lakes. Because none of the seismic lines crossed lakes in the vicinity of pushup concentrations, the seismic crews were requested to drill and load additional holes on two of the study lakes (Lake E and Lake G). For the first experiment (Lake E), Imperial Oil was requested to place a 50 lb (22.6 kg) charge in the shot hole. This charge, which was considerably heavier than the 15 lb (6.8 kg) charge presently being used by Imperial Oil, was selected to represent the upper limit of charges that have been used in seismic programs on the Delta. This was reduced to 25 lbs (11.3 kg) for the second experimental blast on Lake G. In both cases charges were placed at the bottom of 60 ft (18.2 m) shot holes, about 8 m from the lakeshore (Figures 3 and 4).

On both lakes, geophones and hydrophones were fixed at intervals (15, 30, 45, 60, 75, 90, 120 and 150 m) along a line perpendicular to the shore, leading away from the shot hole. Holes were drilled in the ice and hydrophones were suspended in the water 1.5 m below the surface of the ice (or about 30 cm below the bottom of the ice layer) (Photo 3); the hydrophone positioned at the closest hole to the blast site was suspended 0.9 m below ice level. Geophones were placed on the ice surface opposite each hole, as well as in pushups and artificial bank-burrows. Measurements of ice thickness, water depth and snow depth were made at each location.

Muskrats taken from specially set traps on study lakes were subjected to blasts of specified intensity, in simulated bank-burrows, in pushups, and in water at predetermined depths and distances from the shot hole. Control animals were kept several hundred yards from the blast site. Animals placed in bank-burrows (Photo 4) and pushups remained in these locations for several minutes, and were barricaded in to prevent escape. Animals experimentally exposed to blast effects under water were held in cages and lowered into the water (Photo 5) where they remained for about 45 seconds. All animals were checked prior to and after the blast for visible signs of injury or defect and for apparent stress associated with handling and holding procedures. Before and after animals were positioned for the blast, they were housed in cages in a heated box. This box was also used to transport animals from the heated tent where they were held for several hours prior to the blast, and to the helicopter which was waiting to transport the animals to the Inuvik Scientific Research Laboratory, where necropsies were performed.

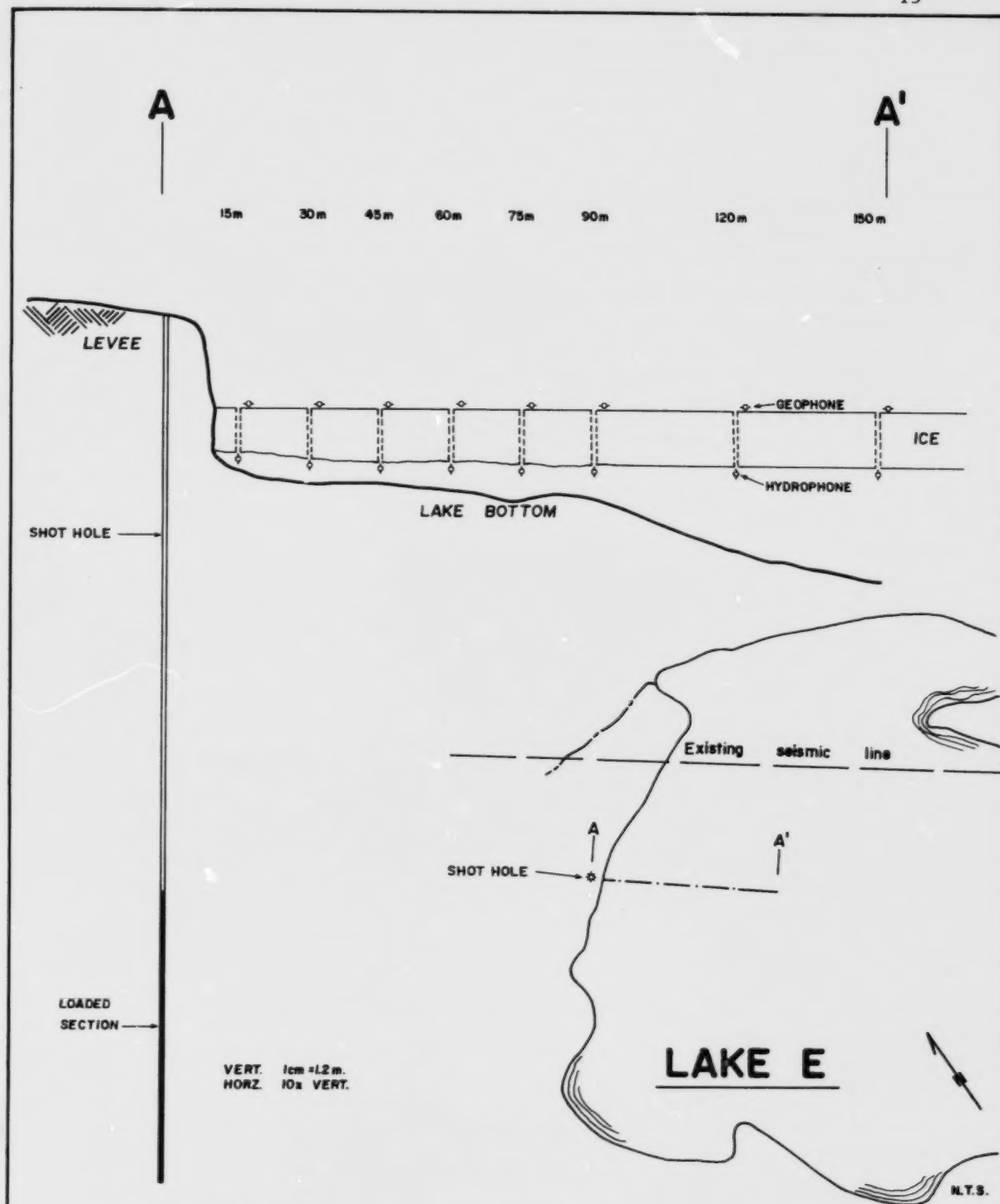


Figure 3

Placement of seismic recorders for experimental blast on lake E.

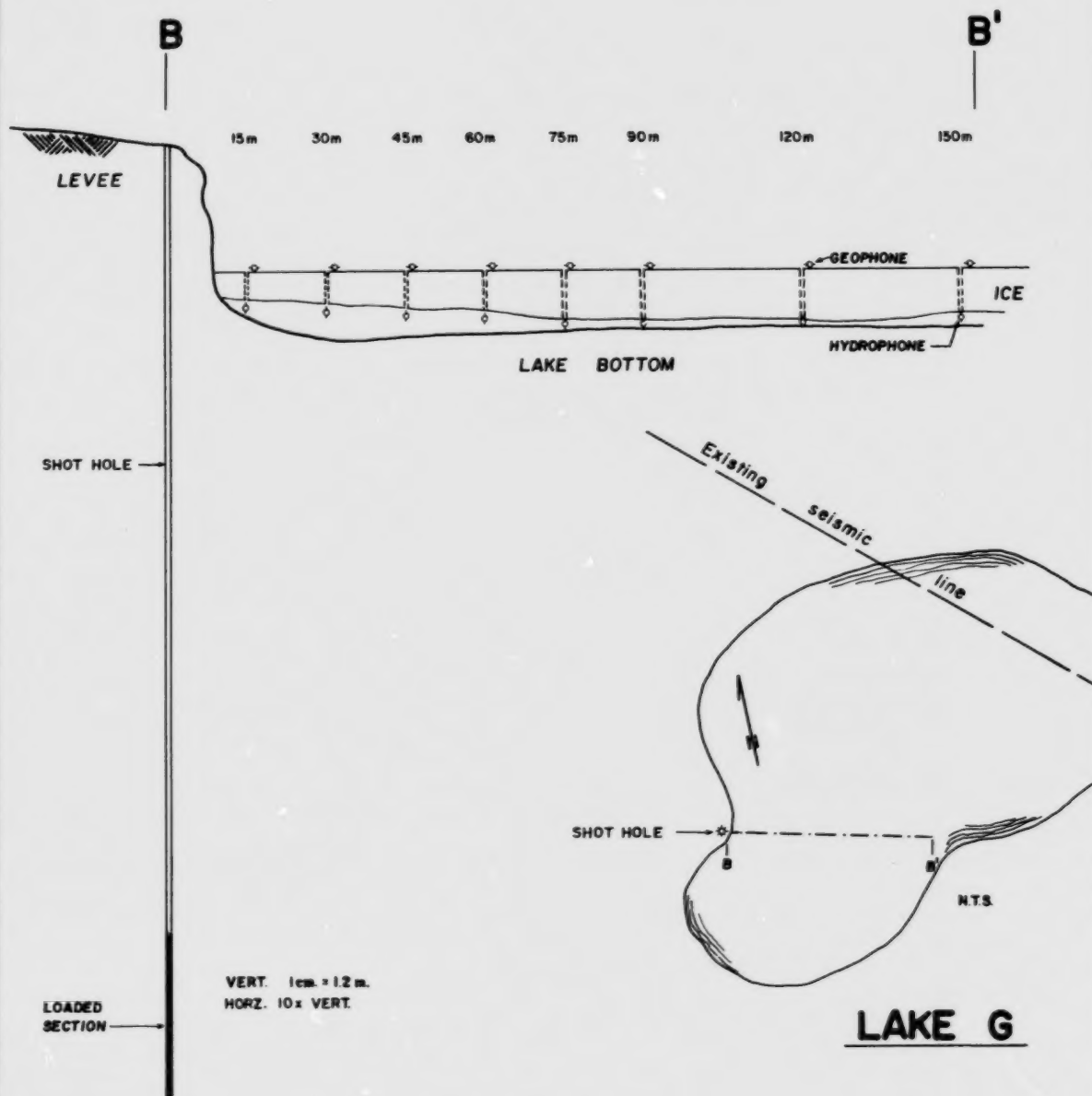


Figure 4

Placement of seismic recorders for experimental blast on lake G.

6.1.2 Pathological and Histological Examinations

Pathological examination following the blast comprised a clinical examination to ascertain the animals' general physical condition and behavior, a gross post mortem examination, and a microscopic examination of tissues. Animals were euthanized by intravenously injecting an overdose of barbituates (Barb-lethal, Hauer-Lockhart Laboratories) into the tail vein, or by administering an overdose of ether. The pelt was removed, and the animal opened ventrally. The viscera were observed, and liver, lung, kidney and adrenal gland were weighed and preserved in 10% buffered formalin for later microscopic examination. The tympanic membrane was exposed by careful dissection of the ear canal and surrounding bony structures. The middle ear was also exposed in this manner, as was the brain. Following inspection, the brain was removed and preserved for histological examination.

Histological examination of tissues was performed by routine tissue processing, and hemotoxylin and eosin staining of paraffin sections. Microscopic evaluation of the lipid status of adrenals was performed on frozen sections with an oil red O fat stain. Microscopic examination of adrenals was performed to evaluate response to stress. Adrenal glands are reported to hypertrophy in response to stress, and to exhibit alteration of lipid content (Selye 1957, cited by Barrington 1975).

Digestive tracts were preserved for later identification of endoparasites for the purpose of further evaluating general physical condition of specimens prior to the blast, and their relative vulnerability to physiological stress.

6.1.3 Other Necropsies

Additional post mortem examinations were performed on animals collected during a steel-trapping program. Carcasses were delivered to the Inuvik Research Lab within a few hours of death for necropsy. Body weights of animals were obtained in the field. Measurements taken in the lab included total length, tail length, fresh weights of each adrenal gland, and in males, weights of testes. Adrenals, testes, uterine tracts, eyes (for possible later aging by eye lens weight) and samples of abnormal tissue (including sections of liver infected with *Taenia* sp.) were fixed in 10% formalin. One adrenal gland from each animal was quick frozen for later analysis of lipid content. Carcasses were then frozen whole.

6.2. Population Studies

6.2.1 Livetrapping

Livetrapping was conducted on four lakes (Lakes E and E₁ and F and F₁), to ascertain population levels before and after seismic blasting. A trapping session comprising six trapping periods, was initiated on each lake 10 to 15 days before blasting. A second session comprising three periods, was conducted two days before blasting to determine effects of trapping itself on population levels at Lakes E and E₁. It was not possible to execute plans for a similar trapping session on Lakes F and F₁ because of the unexpected early arrival of seismic crews to Lake F. Post seismic population levels were determined from steel-trapping results.

National 6" x 6" x 19" collapsible single door live traps were used. Traps were set by cutting away one side of the pushup and placing the trap flush with the opening, so that the pullout platform was between the plunge hole and the trap door. The trap was enclosed on all sides by thick styrofoam insulation (Photo 6) cut to fit the exact dimensions of the trap (after Hawley and Hawley 1975). Attempts to seal traps from cold drafts included pasting amounts of slush and wet mud around the junction and any suspected cracks. After replacing traps, insulation, and mud, the pushup was covered with a thick layer of light snow to further insulate it and the trap. Despite all efforts, traps were constantly being plugged with vegetation and mud, presumably to eliminate drafts, when ambient temperatures were below about -25°C.

Muskrats held captive in traps (sometimes for twelve hours or more) appeared to suffer no resultant ill effects. Animals were removed from traps by coaxing them into a wire mesh holding cone (Westworth 1974) fitted with a moveable floor. Upward pressure on the floor rendered the muskrat relatively immobile allowing tagging, sexing and measuring (Photo 7). Animals were tagged on both ears with National self-piercing, fingerling tags (Size 1, Style 1005). Weights were obtained by weighing the muskrat in the trap, and subtracting the weight of the empty trap. An Ohaus brand spring scale was used to obtain weights to the nearest 10 grams. Tail length (from anus to tip) and total length were recorded. Sex was determined by noting the presence or absence of a penis as determined by palpating the urethral papilla (Baumgartner and Bellrose 1943). We were hesitant to estimate ages of muskrats in the field. Methods of determining age of live muskrats have not proven to be satisfactory for aging animals captured in late March and April, at a time when juveniles approach adult weights and sizes, and many sub-adults are coming into breeding condition (Baumgartner and Bellrose 1943, Beer and Meyer 1951, Fuller 1951a, Olsen 1959, and Hawley and Hawley 1975).

Following the seismic operation the cooperation of a local trapper was secured to systematically trap eight of the 14 lakes investigated in this study (Lakes D, D₁, E, E₁, F, F₁, G and G₁). A total of six trap sets were made at pushups on each of the lakes,

except on Lakes F where four checks were made. When weather permitted, traps were checked twice daily; otherwise daily checks were made.

6.2.2 *Reproductive Examinations*

Muskrats were again collected during the spring field season (June) in order to ascertain whether reproductive rates differed between lakes exposed to seismic activity and control lakes. Animals were collected with a .22 calibre rifle; field workers selectively shot females, if it was possible to differentiate sexes. Additional carcasses were provided by a local trapper. Muskrats were necropsied within a few hours of death. Each was checked for general physical condition (fat storage, organ condition, injuries, etc.), standard body measurements were taken (body weight, total length and tail length), and eyeballs were fixed for later weighing of lenses and aging. Counts were then made of numbers of corpora lutea, embryos, placental scars and embryo resorptions.

6.3 *Activity Studies*

6.3.1 *Pushup Surveys*

Seven lakes on which active pushups were found were selected as experimental lakes (Lakes B through G). All were bisected by a seismic line and would be subject to nearshore blasting. Seven control lakes (Lakes B₁ through G₁) off the line were also selected. An effort was made to pair lakes on the basis of size and pushup density although this was often difficult due to the scarcity of suitable lakes in this area.

Each pushup was marked and its position plotted on large-scale maps. In most cases, snow depth at each pushup was recorded. Plunge holes of pushups are kept from freezing by continuous use, consequently, a frozen plunge hole is indicative of an abandoned or "inactive" pushup. The condition of pushups on the study lakes was determined by probing for the plunge holes with a narrow stainless steel rod mounted in a wooden handle. The first pre-seismic check was made when the pushup was found and marked (20 to 28 March); the second was near the time of blasting (corresponding control lakes checked at same time); the post-seismic check was made about one week after the second check. Several weeks after seismic activity ceased (28 to 30 April), six pairs of lakes were revisited (time and difficulty of travel over the

melting snow prevented surveying Lakes C and C₁). All pushups that had by this time appeared through the diminishing snow layer, were plotted on maps and checked for activity. Appendix III presents maps of each lake with all known pushups plotted. The status of each is indicated, as determined at the time last visited. Measurements of ice thickness, water depth and snow depth were made at each lake. Samples of 20 pushups were collected from each lake and analyzed in the laboratory. It was hoped that qualitative differences in aquatic flora could be detected from these data.

6.3.2 Pushup Activity Monitoring

Data regarding activity patterns of muskrats were obtained through the installation of a system of electrical switches in pushups connected to a chart recorder, after the design of Hawley and Hawley (1975). A battery (12 v. auto) and the recorder (esterline Angus 20 point Common Return, Model A620x Event Recorder) were housed in a wooden box heated above freezing by a small catalytic heater. Components of the system were linked together using two-strand electrical bell wire. When possible, probe switches were installed when pushups were opened during livetrapping operations.

Pushup activity monitoring was conducted on two study lakes (E and G) to correspond with direct effects experiments. Considerable problems were encountered with this method, primarily because of freezing of the probe to the inner surfaces of the pushup and the formation of ice between the electrical contacts. It was found that even checking the probes daily did not alleviate the problem entirely. We feel that the technique requires considerable refining before it can be used with confidence.

6.3.3 Telemetry

Radio telemetry was attempted in order to track the movements and activities of muskrats on Lake G before and after the experimental blast. Our efforts proved unsuccessful for a number of logistical reasons and no usable data were gathered.

7.0 RESULTS AND DISCUSSION

7.1 Direct Effects

7.1.1 *Pressure Changes Associated with Seismic Blasts*

During the experimental blasts on Lakes E and G, arrays of hydrophones and geophones aligned perpendicularly to the shot hole, recorded instantaneous water pressure and instantaneous particle velocity respectively. Water pressures measured by hydrophones during Experiments 1 and 2 are given in Table 3. It is not yet clear whether data measured by the geophones can serve as a useful index of the shock wave intensity; consequently, no assessment of these data will be made at this point.

During the test blast on Lake E, pressure data were not recorded for hydrophones located at distances of 15, 30, 45 and 60 m from the shot hole. This situation was the result of overloading the particular "gain" at which the recording unit was set, resulting in a distortion or "squaring" of the amplitudes recorded on the seismograph. On Lake G, in the second experiment, the charge size was reduced to 11.3 kg from 22.6 kg. Again overloading of the recording unit prevented us from obtaining data from hydrophones located 15 m and 30 m from the shot hole. One can however, derive theoretical pressure values by using the relationship that in water peak pressure decays inversely as the first power of the distance (Hubbs and Rechnitzer 1952). Thus at 15.2 m, one could expect a water pressure value of about .004 psi (J. Hogg pers comm). In comparing the pressures of Experiments 1 and 2, very similar values are common to both lakes. Based on the amount of explosives used, it is expected that the pressure values on Lake E would be slightly larger than on Lake G; and that the increase would be in proportion to the one-third power of the charge (Hubbs and Rechnitzer 1952). During the experimental blast on Lake G, some of the explosive energy in the shot hole blew out through the top; consequently, it can be assumed that less energy was expanded into the surrounding medium. For this reason even smaller water pressures could have been expected in Lake G than in Lake E (J. Hogg pers comm). A simple explanation of these varied results cannot be offered due to the complex interrelationships of ice thickness, water depth and the nature of the lake bottom.

During Imperial Oil's seismic program, anti-alias, high cut filters were used in the recording units to eliminate high frequencies in order to record data digitally. Consequently, the amplitude and the frequency of the recorded signal may have been distorted when signals received were beyond the optimal frequency range of the filters (J. Hogg pers comm).

Table 3. Water pressure changes recorded during experimental blasts on Lakes E and G.

Hole No.	Distance From Shot Hole (m)	Pressure Change (psi)	
		Lake E	Lake G
1	150	0.00043	0.00021
2	120	0.00053	0.00054
3	90	0.00116	0.00111
4	75	0.00390	0.00074
5	60	ND	0.00218
6	45	ND	0.00103
7	30	ND	ND
8	15	ND	ND

In assessing the effects of pressure changes on an animal, the rate of pressure change as well as the peak pressure should be taken into account. For example, damage may occur to an animal due to low pressures if they occur during a very short period of time.

Geophones were placed on the ice surface at the same locations as hydrophones; as well as on, and in pushups, and in simulated bank-burrows. It was hoped that the data received from the geophones would indicate the degree of vibration sustained by the pushups and bank-burrow. However, it is now apparent that the recorded data cannot be transposed into units of vibration and that the desired comparisons cannot be made.

7.1.2 Experiment 1 - Lake E

The experimental charge on Lake E was detonated at 0912 on 4 April, 1976. The overnight low had been -24°C , the sky was clear and there was no wind. Animals were inspected before the experimental procedure for any signs of injury or unusual stress. One animal was found to have a partially frozen tail and seemed stressed. It was therefore decided not to use this individual for experimental purposes. All other animals appeared healthy.

Two animals were barricaded in a simulated bank-burrow, two in a pushup in which the plunge hole had been covered with wire mesh to prevent escape, and two each were suspended in water 15 and 30 m from the shot hole. Animals were lowered into the water so that the cages were just under the lower surface of the ice (about 1 m). They remained in this position for 45 seconds. The blast was felt as a heavy thump accompanied by the sound of cracking ice. An observer stationed at an opened pushup could detect no change in water level within the pushup.

The animals were quickly removed from their positions, placed aboard the waiting helicopter and transported to the lab where post mortems were performed. The following results were recorded.

Submerged 15 m from shot hole:

Animal No. 2. Body weight 785 g. Juvenile female. Tympanic membranes were intact but a thin film of free blood was present, emanating from suture lines of bone forming the medial wall of the middle ear. A few petechial hemorrhages were present in the lungs. Congestion was present in the meninges.

Animal No. 3. Body weight 785.5 g. Juvenile male.
Hemorrhage in retro-peritoneal fascia over kidneys
associated with emphysema in these tissues. Vena cava
was markedly dilated. Ear drums were normal.

Submerged 30 m from shot hole:

Animal No. 4. Body weight 836.5 g. Male.
No lesions were found. Lungs were inspected while
heart and respiratory movements were still functional.
No hemorrhages or congestion present.

Animal No. 5. Body weight 730.4 g. Juvenile female.
Lungs showed hypostatic congestion and small petechial
hemorrhages. Subcutaneous hemorrhages were present over
the dorsal caudal back area which were interpreted to be
handling injuries.

Placed in simulated bank-burrow:

Animal No. 7. Body weight 1020.0 g. Female.
Difficulty was experienced in intravenous euthanasia.
A sero fibrinous peritonitis developed within several
minutes of intraperitoneal injection of 0.5 cc of barbituate.
Hemorrhages and congestion were present in the lung.
Ears were unaffected.

Animal No. 8. Body weight 772.2 g. Juvenile male.
Hemorrhage and congestion of lungs, very slight hemor-
rhage of suture line of bones forming the wall of the
middle ear.

Placed in pushup:

Animal No. 9. Body weight 722.0 g. Juvenile female.
Many sub-pleural hemorrhages. No other signs apparent.

Animal No. 10. Body weight 926.1 g. Adult female.
No lesions were observed in this animal.

Control (captured at same time as test animals):

Animal No. 6. Body weight 806.4 g. Male.
Hemorrhages were present over apical lobe of lung.
There were no other significant or notable changes,
apart from congestion in the meninges.

Animal No. 11. Body weight 690.4 g. Juvenile male. Carcass was very emaciated and the tail had been frozen. The last 6 cm of its tail had been chewed off. There was no brown fat. The stomach and intestines were empty. The adrenals were greatly enlarged.

Control (captured and necropsied on 3 April):

Animal No. 1. Body weight 804.0 g. Male
This animal was euthanized by intraperitoneal injection of 2 cc of barbiturates. The peritoneal cavity was opened within five minutes and there was a severe peritonitis characterized by yellow fibrinous effusion adhering the abdominal viscera. There was a single large pulmonary ecchymosis. The eyes were pasted shut by a seromucinous conjunctival secretion.

Control (captured 3 April, necropsied 5 April):

Animal No. 12. Body weight 1043.0 g. Adult male.
This animal was captured a day before the test blast and kept caged in the laboratory as a stressed control. The adrenals were noticeably larger than those of No. 1 but there were no significant lesions.

7.1.3 Experiment 2 - Lake G

The experimental charge on Lake G was detonated at 0940 on 10 April, 1976. The overnight low had been -9°C ; the day was clear and fairly calm. As with the first experimental blast, animals were inspected for injury and stress; all appeared in good condition.

Three animals were introduced to the simulated bank-burrow constructed the day before, and barricaded against escape. Preparations were made to lower three other animals into a hole drilled through the ice 15 m from the shot hole. As before, the cages were lowered just below the bottom surface of the ice, where they remained for approximately 45 seconds. In contrast to the first experimental blast (where the charge was twice as large), this detonation was loud, blowing dust and fragments of frozen soil more than 20 m into the air. This is of fairly common occurrence during seismic operations and results from insufficient tamping after the charge is laid.

Again the animals were removed from their positions and transported by helicopter to the laboratory facilities in Inuvik for post mortem examination. Following are the results from those examinations.

Submerged 15 m from shot hole:

Animal No. 13. Body weight 1095.2 g. Adult female. Slight hemorrhaging was noted along bony suture lines of both middle ears. There were no other lesions.

Animal No. 15. Body weight 777.1 g. Juvenile female. Signs of congestion on dorsal surface of lung. Slight hemorrhage along suture line of both middle ears.

Animal No. 17. Body weight 828.5 g. Juvenile female. No lesions observable in this animal.

Placed in simulated bank-burrow:

Animal No. 14. Body weight 910.0 g. Male. Numerous petechial hemorrhages apparent in the lung. Hemorrhaging present along bony suture line of one middle ear.

Animal No. 16. Body weight 920.0 g. Male. Numerous petechial hemorrhages present in lung together with generalized congestion. Hemorrhaging apparent along suture line of left middle ear.

Animal No. 18. Body weight 691.8 g. Juvenile male. Very slight pleural hemorrhaging noted. No other lesions present.

Control (captured at same time as test animals):

Animal No. 19. Body weight 996.0 g. Female. No lesions or other effects apparent. Animal appeared stressed while in captivity. Lethargy and refusal to eat or drink were accompanied by somewhat enlarged adrenals.

Animal No. 20. Body weight 928.6 g. Male. This animal also appeared stressed with signs of lethargy and refusal to eat or drink. These control animals were not examined until 24 hours after the blast so were subjected to stress of confinement. Adrenals were slightly enlarged. No evidence of blast effects.

Animal No. 21. Body weight 1060.6 g. Female.
Congestion apparent on right median lobe of lung.
Animal did not outwardly appear stressed (ate and drank throughout), but adrenals were greatly enlarged, and fat deposits were only moderate.

All animals were in good physical condition with ample supplies of body fat and brown fat. Parasitological examination revealed a minimal load of parasites and they did not appear to affect the physical condition of the animals.

Histological examination of various tissues collected from the above animals revealed no additional lesions.

Interesting biological and pathological responses were evident in muskrats sacrificed at the time of the first experimental blast. Euthanasia was attempted in the least stressful manner possible and intravenous barbituates resulted in rapid death. In spite of this, agonal hemorrhages in the lung both parenchymatous and sub-capsular, were of common occurrence in both control and experimental animals. Marked congestion and discoloration of the lungs resulted within two to three minutes following death. It was apparent that assessment of hemorrhage and congestion in the lungs would not provide a valid measure of trauma to these animals.

Similarly, congestion of the meninges was marked and apparently resulted from placing animals on their backs for post mortem examination. Congestion of the meninges partially in the tentorium ossci over the cerebellum was present in all animals.

Intraperitoneal injections of barbituates (used only for the first experiment) produced an unusually rapid and violent tissue reaction. The animals produced an excessive exudation of fibrin and fluid, giving the appearance of a well established peritonitis in less than five minutes following injection. Such an ability to mount an acute inflammatory response, indicates an unusual capacity to respond to stress and injury (this has probably developed to cope with the adverse environment in which they live). These animals also seem to have a very placid nature which would suggest that after an initial rapid response to stress, the incident would be quickly forgotten provided the stress or stimulus was removed.

In domestic animals intravenous barbituates produce a huge engorgement of the spleen. Splenomegaly was not noted in these muskrats, but following euthanasia, the posterior vena cava was extremely dilated and congested with blood. This suggests that the posterior vena cava serves as a shock organ in these animals.

The principal lesion found with exposure to blasting was hemorrhage emanating from suture lines of bone involved in forming the medial wall of the middle ear. The amount of hemorrhage was minimal and no altered behavior or clinical signs could be associated with lesions. Histologically, there were no capillary hemorrhages in the brain indicating deeper injury. In one animal diffuse peri-renal retroperitoneal hemorrhage was present. This lesion is equivocal as dissection in this area commonly incised blood vessels which flooded the area and produced a similar appearance to hemorrhage. Although it appeared that this hemorrhage (in Animal No. 3) was the result of blast injury, it cannot be stated positively.

As the muskrat is adapted to frequent underwater existence, the lacrimal glands secrete a seromucinous substance that encrusts around the eyelids when the animals are kept alive in a centrally heated room. This gives the appearance of conjunctivitis but was considered here to be a normal phenomenon. Also, as a probable adaption to diving and high pressure changes, the tympanic membrane is strongly constructed with spicules of cartilage and bone reinforcing a rigid membrane. Its appearance suggests that a substantially greater force would be required to rupture this membrane than that necessary to rupture the ear drum of a primarily terrestrial animal.

These experimental findings indicate that animals extremely close to shot holes when they are detonated are apt to suffer some pathological effects. Of five animals examined after exposure to blasting in a simulated bank-burrow, three showed signs of hemorrhaging along suture lines of the middle ear and all five sustained slight lung damage indicated by petechial hemorrhaging. In these animals, ear damage occurred on one side only, suggesting that orientation may have been a factor. Of five animals subjected to blasting while submerged in water 15 m from the shot hole, three experienced damage to the middle ear, but only one showed effect to the lung. In the cases of animals sustaining ear damage here, orientation did not seem influential, as both ears were affected. Of animals exposed to blasts while restrained in pushups or submerged at distances greater than 15 m, only one case of petechial hemorrhages in the lung was encountered. Control animals were without lesions. Subcutaneous lesions were not present in any of the injured animals and the effects observed apparently did not arise from animals striking cage or burrow walls.

Although these results indicate that animals in close proximity to blasts are likely to sustain some injury, it is believed that the degree of injury was sufficient only to cause transitory pain and discomfort, but that it would not produce permanent injury, and animals would recover rapidly.

Because of the failure of apparatus to register accurate pressure readings at stations close to shot holes, the absolute pressure

changes which caused injury cannot be provided. We can however, deduce that the greatest pressure reading recorded in this study (.00390 psi) was not sufficient to cause effect. As will be discussed in subsequent sections, more sophisticated instrumentation than was used in this study would be required to provide specific information regarding injurious pressure changes and noise levels.

7.1.4 Evaluation of Adrenal Response

The adrenal glands are endocrine organs which appear to release hormones which stimulate the cells of the zona fasciculata (middle layer of the adrenal cortex) to release cortisol which produces heightened physiological function necessary to cope with increased physical activity often accompanying stress. Changes take place in the adrenal cortex associated with this stimulation. These are the accumulation and breakdown of cortisol lipid precursors, and cellular hypertrophy with specific increased thickness of the zona fasciculata. These factors were evaluated by oil red O fat stains for lipid accumulation, and histologic evaluation of cellular size, congestion of blood vessels in the adrenal cortex, and measurement of zone thickness.

Adrenal glands of all necropsied animals were divided into three categories:

- (I) from animals exposed to experimental blasts and necropsied within a few hours of this exposure,
- (II) from animals trapped at lakes where routine seismic blasting was conducted,
- (III) from animals trapped at lakes where no blasting of any kind was done (control animals). The latter two categories of animals were trapped and necropsied one to two weeks after cessation of seismic activity.

The only measurement found valid in assessing stress in this study, was increased weight of the glands, and increased size of the zona fasciculata. The phenomenon was apparent in those animals known to be acutely and severely stressed. Stains for fatty infiltration and evaluation of congestion and cellular hypertrophy did not reveal meaningful changes (Table 4). No increase or depletion of lipid could be demonstrated in any of the adrenal glands by the fat stains used. No differences between Categories I and III could be demonstrated from the data for any of the parameters evaluated.

Adrenal response was also used to measure long-term or sustained stressful effects of the seismic explosions. The parameters of size, cellular hypertrophy, fatty infiltration and congestion were measured but no significant alteration could be found between the groups

Table 4. Results of histological evaluation of adrenal glands.

Category	Adrenal Weight (g)	S*	H	FI	CH
I	0.093	20	1	-	3
	0.092	18	1	-	2
	0.057	17	2	-	1
	0.139	21	3	-	1
	0.155	27	1	-	4
	0.236	32	4	-	4
	$\bar{X} =$	22.5	2.0	-	2.5
II	0.115	22	2	5	2
	0.064	15	1	3	1
	0.064	15	1	5	1
	0.124	23	4	2	3
	0.058	13	1	3	1
	0.127	24	3	1	5
	0.106	19	1	1	2
	0.087	17	2	1	2
	0.086	23	2	5	2
	0.108	20	2	1	2
	0.109	18	2	4	2
	0.177	25	6	4	6
	0.054	17	1	1	1
	0.087	23	1	1	3
	0.075	18	2	1	2
	$\bar{X} =$	19.4	2.1	2.5	2.3
III	0.062	15	1	1	1
	0.070	20	2	1	2
	0.220	33	3	3	4
	0.070	20	1	1	3
	0.065	14	1	1	2
	0.081	18	2	1	2
	0.106	20	2	4	2
	0.111	23	2	4	3
	0.140	30	1	3	4
	0.118	33	4	5	3
	$\bar{X} =$	22.6	1.9	2.4	2.6

S* = arbitrary numerical size of adrenal cortex

H = hemorrhage and congestion

FI = fatty infiltration

CH = cellular hypertrophy

(Categories II and III). This indicates that either examination of adrenals was inappropriate for measuring longer term stress in muskrats, or that the animals did not, in fact, experience any prolonged stressful situation.

It was ascertained, using animals known to be stressed (eg. several days of captivity, poor physiological condition, injury), that acute and constant stress resulted in adrenal hypertrophy (Photos 8 and 9). Adrenal weights twice and three times the average were found after two days of captivity. This response was surprisingly rapid. It would be impossible however, to detect stress of this type in Category I animals because of the extremely short time span between the experimental blast and necropsy. In Category II animals on the other hand, the time span between routine seismic blasting and necropsy was one to two weeks, possibly long enough for animals briefly stressed to resume a more typical endocrine balance and for enlarged adrenals to return to normal size. It is therefore possible that stressed animals may have evaded our detection. Another complicating feature of the use of adrenal hypertrophy as a barometer of stress resulting from seismic activity, is that with the onset of breeding, increase adrenal size is to be expected, especially in females. Adrenals from females captured in June were three or four times the size of the largest ones found in April.

Results of the analysis of adrenal weights of Category II and III animals are presented in Table 5. It is apparent from these data that seismic activity had no effect on mean adrenal weights. It is possible however, that individual animals may have been affected by blasting at experimental lakes. This would be reflected in higher frequencies of animals with enlarged adrenals on these lakes. Figure 5 does not indicate such a trend.

7.2 Population Studies

7.2.1 *Effect of Seismic Activity on Population Levels*

Population estimates based on livetrapping and steel-trapping programs in Lakes E and F, and their corresponding control lakes, were derived using the Schnabel estimator (Overton and Davis 1969; Chapman and Overton 1966). The assumptions necessary in using this estimator appear to be tenable since, in winter, recruitment and dispersal are not occurring and the population can, for practical purposes, be considered closed.

The results indicate that no significant changes occurred in population levels on any of the four lakes tested following seismic blasting (Table 6). Confidence limits calculated according to the method described by Chapman (1948) and Chapman and Overton (1966) are quite wide and show considerable overlap.

Table 5. Effects of seismic activity on weights of adrenal glands.

Lake	$\bar{X}$ Body Weight (g)			$\bar{X}$ Adrenal Weight (g)			% Body Weight (g)		
	Males		Total	Males		Total	Males		Total
		Females			Females			Females	
D	1027(16)	952(14)	992(30)	0.071	0.077	0.074	0.0069	0.0080	0.0074
E	1089(19)	976(20)	1031(39)	0.091	0.088	0.090	0.0085	0.0089	0.0087
F	1104(12)	973(11)	1041(23)	0.097	0.111	0.104	0.0089	0.0114	0.0101
G	1020(2)	1023(6)	1022(8)	0.077	0.112	0.103	0.0075	0.0105	0.0097
All Experimental	1070(49)	974(51)	1021(100)	0.085	0.093	0.089	0.0080	0.0094	0.0087
D ₁	1052(16)	1018(19)	1034(35)	0.098	0.105	0.102	0.0094	0.0102	0.0098
E ₁	848(8)	865(7)	856(15)	0.076	0.119	0.096	0.0090	0.0135	0.0111
F ₁	1115(14)	943(10)	1043(24)	0.104	0.098	0.102	0.0097	0.0107	0.0101
G ₁	1250(3)	1156(3)	1203(6)	0.101	0.115	0.108	0.0081	0.0099	0.0090
All Control	1048(41)	982(39)	1016(80)	0.096	0.106	0.101	0.0093	0.0109	0.0101
All Lakes	1059(90)	977(90)	1018(180)	0.090	0.099	0.095	0.0086	0.0100	0.0093

Parentheses denote sample sizes

Figure 5

Frequency distribution of adrenal gland weight classes.

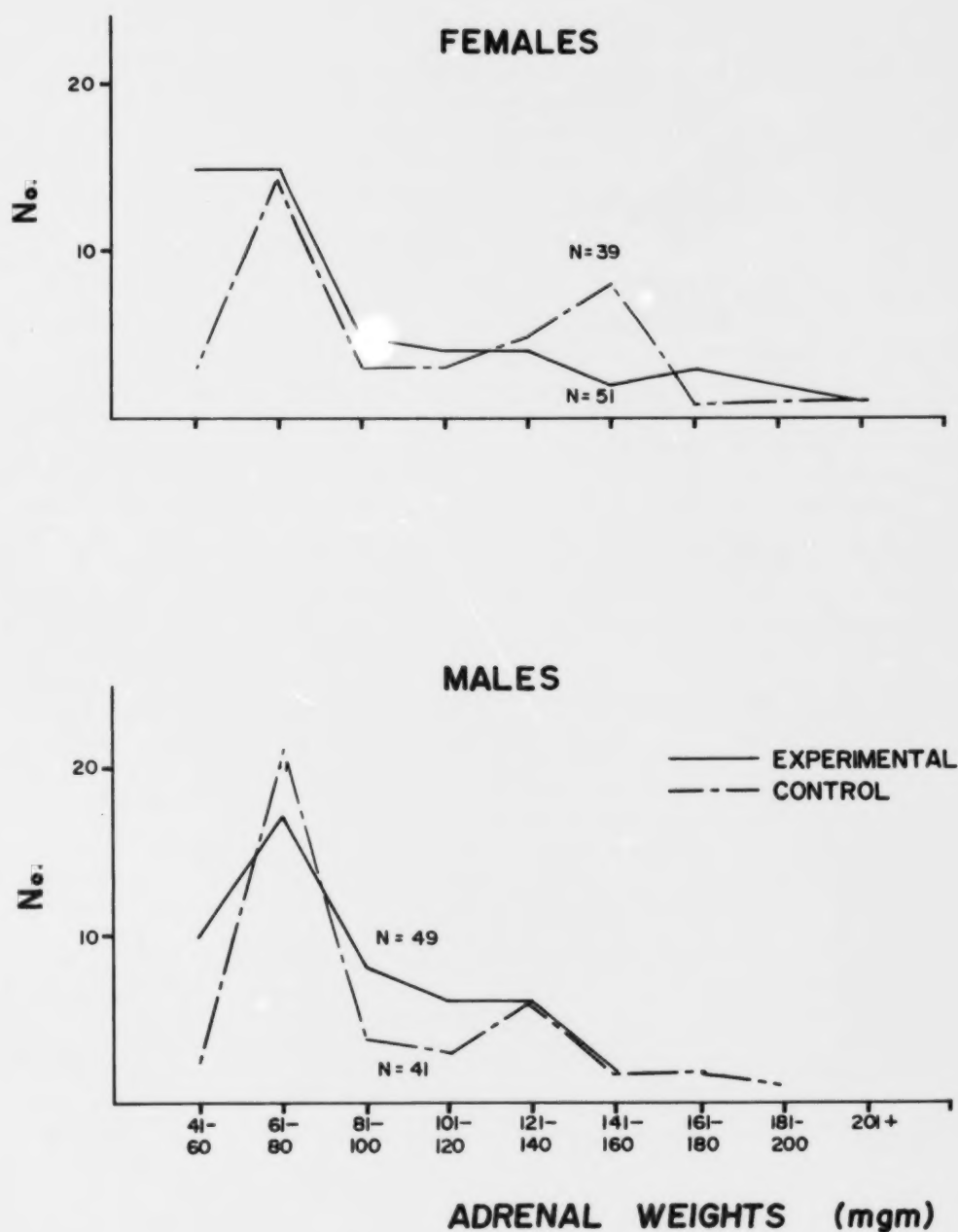


Table 6. Effect of seismic activity on population sizes

Lake	Population Estimate* (95% Confidence Limits)	
	Pre-seismic	Post-seismic
E	N=54 (28.62 $\leq$ N $\leq$ 106.59)	N=51 (34.05 $\leq$ N $\leq$ 76.21)
E ₁	N=34 (18.80 $\leq$ N $\leq$ 62.51)	N=29 (19.03 $\leq$ N $\leq$ 44.83)
F	N=27 (15.00 $\leq$ N $\leq$ 49.88)	N=30 (20.47 $\leq$ N $\leq$ 45.82)
F ₁	N=38 (5.47 $\leq$ N $\leq$ 1481.16)	N=23 (12.01 $\leq$ N $\leq$ 44.72)

*Calculated using the Schnabel Method (Chapman and Overton 1966).

Two additional points should be considered with respect to these population estimates. The first is that, while all known pushups were livetrapped on each of the lakes, the snow cover in March prevented us from locating all of the pushups. Consequently, only a portion of the population may have been sampled in each case. Based on a later pushup survey in April when the snow cover was diminished, the proportion of active pushups found and trapped ranges from 53% on Lake F to 90% on Lake F₁. This is not considered important in comparing *changes* in population level because only those pushups initially livetrapped were subjected to post-seismic trapping. The second point is that the sampling techniques differed in pre-seismic and post-seismic trapping. The Schnabel estimator is normally used in situations involving livetrapping throughout the sampling period. A critique of our methodology, along with the computed Schnabel tables for each of the study lakes, is found in Appendix II.

7.2.2 Reproduction

Female muskrats were collected from experimental and control areas during June 1976, and post mortem examinations were subsequently performed. Data regarding reproductive performance of these animals is presented in Table 7. Comparison of the proportion of females that were pregnant, from experimental and control areas, showed only minor differences ($\chi^2 = 0.44$, $p > 0.05$). Mean numbers of embryos (and placental scars) per productive female were also similar between experimental and control groups (8.18 and 8.61 respectively). The number of young per litter deduced from these data provided an overall average of 8.06 (after resorptions were taken into account). This average is similar to that found by Stevens (1955) in the Mackenzie Delta (8.4 young per litter), and somewhat higher than those calculated by Westworth (1974) for complete litters of nestlings (7.2 and 7.5 young per litter in 1970 and 1971 respectively) in the Peace-Athabasca Delta.

Resorption of embryos was found among both experimental and control groups (Photo 10), and although females from experimental areas showed slightly higher averages (0.55 per gravid female, as opposed to 0.31 for females from control lakes), this difference was not significant ($\chi^2 = 0.22$, $p > 0.05$). The incidence of resorption found during this study (5%) is similar to that recorded by Hawley and Hawley (1975) during 1963 when population levels on the Delta were high.

Table 7. Reproductive performance of muskrats collected from Study Area lakes in June 1976.

	Treated Lakes	Control Lakes	Total
Total no. females	16	23	39
No. gravid	11	16	27
% gravid	68.8	69.6	69.2
No. with resorbing embryos	4	3	7
% with resorbing embryos	36.4	18.8	25.9
No. with placental scars	0	2	2
% with placental scars	0	8.7	5.1
No. gravid or with scars	11	18	29
% gravid or with scars	68.8	78.3	74.4
No. embryos	90	140	230
No. placental scars	0	15	15
Embryos/gravid female	8.18	8.75	8.51
Embryos and scars/gravid or parturated female	8.18	8.61	8.45
Resorbing embryos/gravid female	0.55	0.31	0.41
Average expected litter size*	7.64	8.33	8.06

* Calculated after resorptions are considered.

7.2.3 Sex Ratios

Information regarding sex ratios of muskrats on the Study Area was gathered incidentally to live and dead-trapping activities. The data indicate a high degree of variability between lakes (Table 8), probably a result of small sample sizes for individual lakes. The ratio derived for the entire sample is 106 males:100 females, slightly lower than that found by Stevens (1955) between 2 March and 14 May (118 males:100 females) in the same general area. Although our sample was not exceptionally large (221), the results of this study do tend to support the findings of other investigators (Stevens 1955, Errington 1966 and Dilworth 1966), that the predominance of males over females at birth approaches nearly equal proportions at the onset of breeding.

7.3 Activity Studies

7.3.1 Incidence of Pushup Abandonment

A total of 272 pushups were located and marked on 14 Study Area lakes during March 1976. This phase of the study was severely hampered by the deep snow conditions present on the delta at that time of year. Results of the final two pushup surveys indicate essentially no change in the number of active pushups on either experimental or control lakes following seismic exploration (Table 9). The largest change observed took place between the two pre-seismic surveys although again the difference was not significant (Mann-Whitney U Test and Kruskal-Wallis Test).

Data were also analyzed to determine the influence of proximity to the seismic line with respect to activity of pushups. These data indicate that an increase in the proportion of active pushups takes place at distances greater than 180 m from seismic lines, however this was significant only for Lake D ($\chi^2 = 10.24$, $P < 0.05$). This difference is significant however, when totals are grouped ($\chi^2 = 14.81$, $P < 0.01$) (Table 10). The difficulty in eliminating other variables which may influence the distribution of abandoned pushups (eg. lake depth & ice thickness), complicates the interpretation of these results, but it does appear that seismic activity influences use of pushups by muskrats within 180 m of lines.

7.3.2 Pushup Utilization

Probe switches were used to electrically monitor the pattern and frequency of utilization of pushups by muskrats. Figure 6 describes calculations made to determine degree of utilization of monitored

Table 8. Sex ratios from experimental and control lakes.

Lake	Sample Size	Males:100 Females
D	30	114
D ₁	35	84
E	54	74
E ₁	27	200
F	33	154
F ₁	28	133
G	8	33
G ₁	6	100
Total	221	106

Samples include all live-trapped and steel-trapped animals.

Table 9. Summary of results of pushup activity surveys.

Lake	% Active Pushups		
	1st Pre-seismic Survey	2nd Pre-seismic Survey	Post-seismic Survey
B	42 (31)	32	42
C	39 (33)	39	45
D	50 (26)	46	42
E	50 (30)	-	43
F	64 (28)	54	46
G	78 (9)	67	56
All Experimental Lakes	50 (157)	44	45
B ₁	52 (25)	44	52
C ₁	50 (16)	53	53
D ₁	50 (34)	47	50
E ₁	56 (16)	56	31
F ₁	100 (10)	100	90
G ₁	50 (14)	50	57
All Control Lakes	56 (115)	54	53

Parentheses denote sample sizes

Table 10. Relationship between proportion of active pushups and distance from seismic line.

Distance	Active	Inactive	% Active	Active	Inactive	% Active	Active	Inactive	% Active
<u>LAKE B</u>									
<60 m	9	9	47	6	15	29	2	7	18
60-120 m	6	18	25	6	12	33	4	11	27
120-180 m	3	11	21	2	11	15	4	9	31
180-240 m	4	3	57	4	2	67	1	1	50
>240 m	0	2	0	8	4	67	7	7	50
TOTAL	21	43	33	26	44	37	18	35	34
<u>LAKE F</u>									
<60 m	6	14	30	2	9	18	25	54	32
60-120 m	5	8	38	3	2	60	24	51	32
120-180 m	5	6	45	3	2	60	17	39	30
180-240 m	7	5	58	2	1	67	18	12	60
>240 m	4	2	67	1	1	50	20	16	56
TOTAL	27	35	44	11	15	42	104	172	37
<u>ALL LAKES</u>									

Data derived from post-seismic survey results and pushups found during the survey of 28-30 April.

Figure 6. Calculation of frequency of pushup use by muskrats before and after experimental blast on Lake G. Calculations were made on the basis of 15 minute time intervals.

PRE-SEISMIC ACTIVITY

7 pushups monitored for 63.75 hours = 446.25 monitored hours
 129.50 hours of this time switches were known or presumed to be inoperative*
 $446.25 - 129.50 = 316.75$ hours of operation
 During this time, 55 separate visits were recorded
 $55 \text{ visits} \div 316.75 \text{ hours} = 0.17 \text{ visits per hour}$
 Or, 4.17 visits per 24-hour period

POST-SEISMIC ACTIVITY

7 pushups monitored for 101.25 hours = 708.75 monitored hours
 318.25 hours of this time switches were known or presumed to be inoperative*
 $708.75 - 318.25 = 390.50$ hours of operation
 During this time, 36 separate visits were recorded
 $36 \text{ visits} \div 390.50 \text{ hours} = 0.09 \text{ visits per hour}$
 Or, 2.21 visits per 24-hour period.

*Includes periods when switches were disconnected and periods when switches were presumed to be frozen (since freezing of switches is thought to be associated with muskrats entering pushups, the time period to last recorded visit has been discounted).

pushups relative to the experimental blast detonated on Lake G on 10 April. The data indicate that while all seven pushups being monitored continued to be visited by muskrats after the blast, there was a 53% decrease in the number of visits per 24-hour period. It is not clear to what degree this decrease is a result of the seismic blast or whether it was caused, in part, by disturbance of pushups by the researchers. The gathering of data was hampered by equipment malfunctions and frequent checks were necessary. The checks required that pushups be opened daily to inspect and reset switches. It was believed by the observers that these frequent disturbances contributed to the temporary abandonment of pushups.

7.3.3 *Activity of Individual Muskrats*

Although attempts were made to radio-equip muskrats on Lake G (prior to the experimental blast) and monitor their activity before, during and after the event, logistic difficulties prevented the gathering of data by this technique. The idea does however, appear to merit consideration in future investigations particularly with respect to interpreting the results of pushup activity surveys.

7.4 Other Effects

Seismic lines and vehicular travel did not appear to affect existing or newly established bank burrows. In three cases, active bank burrows were observed on seismic lines (Photo 11). No abandoned burrows were observed in such locations. It was observed however, that small numbers of pushups were inadvertently destroyed by heavy equipment during lake crossings.

Although tree communities on seismic lines are slow to replace themselves, ground cover including shrubbery is not substantially impaired (Photo 12). Seismic lines cut in March and April displayed continuous ground cover in June. It appears that seismic vehicles using lines (including caterpillar tractors) only temporarily depress this type of vegetation.

8.0 CONCLUSIONS AND RECOMMENDATIONS

- (a) Seismic blasting resulted in comparatively low instantaneous pressure changes in the water. Minor pathological effects were detected in muskrats placed 15 m from shot holes loaded with 22.6 kg (50 lb) and 11.3 kg (25 lb) of Geogel; muskrats subjected to blasts at distances of 30 m and greater were apparently unaffected. The principal lesion found with exposure to blasting was hemorrhage emanating along suture lines in the middle ear. This occurred in muskrats placed both in the water and in simulated bank-burrows during blasting and was apparently influenced by such factors as orientation at the time of concussion and whether or not the shot hole blew out. None of the blast injuries detected were considered capable of causing long-lasting impairment or death.
- (b) Results of livetrapping experiments support the previous conclusion in that no changes in population levels occurred in either experimental or control lakes following seismic blasting.
- (c) We were able to demonstrate that stress, such as that caused by keeping muskrats in captivity or by frequent livetrapping and handling, was associated with increased weight of adrenal glands and hypertrophy of the zona fasciculata. Similar changes were not detected however in muskrats collected from Study Area lakes following seismic blasting. This indicates that, unless adrenals are not a valid indicator of long-term stress in muskrats, animals in lakes exposed to blasting did not experience any prolonged stressful situation.
- (d) Results of monitoring surveys of 272 muskrat pushups indicate that seismic exploration did not significantly increase rates of pushup abandonment on treated lakes. There were, however, indications of localized affect adjacent to seismic lines (i.e. within 180 m). Results of monitoring muskrat activity in individual pushups also suggest a decrease in frequency of use in pushups close to seismic shot holes, however this aspect requires further substantiation before definite conclusions can be reached.
- (e) Collections of gravid females during June 1976 revealed no significant differences in reproductive performance between lakes exposed to seismic blasting and control lakes either in terms of frequency of pregnancy, numbers of embryos or incidence of embryo resorption. These results should be considered with some reservation however, since there is a possibility that many of the animals collected were involved in dispersal movements following spring break-up.

- (f) While small numbers of pushups were inadvertently destroyed by heavy equipment during lake crossings, other activities associated with seismic exploration, including construction of lines, construction of snow ramps at lakeshores and stream-banks, and drilling activities did not appear to seriously threaten the welfare of muskrats. Nothing is known however, of behavioral responses of muskrats exposed to noise from these types of disturbance.
- (g) On the basis of our findings to date, we are able to tentatively conclude that, from the standpoint of muskrat survival, land use regulations and seismic exploration practices as they now exist are acceptable. We recommend that the present regulation prohibiting blasting within 12.2 m (40 ft) of water bodies not be reduced. Consideration should be given to adopting similar regulations regarding size of charges used on the Delta, since the technology apparently now exists for obtaining seismic information using charges of less than 11 kg (25 lb).

9.0 NEED FOR FURTHER STUDY

During the first year of study some of the objectives were not completely answered and certain other problems were identified that would require additional study before their significance can be fully assessed.

While the results of direct effects experiments and population studies enable us to conclude with some confidence that seismic blasting does not directly kill muskrats, considerable differences were observed in the effects of blasting on experimental animals. Replication of these tests would be necessary to more closely define tolerances and individual responses of muskrats to seismic shooting. Further tests should employ instrumentation capable of accurately measuring air pressure changes in bank burrows and in pushups at various distances from shot points.

Data obtained to date on the fate of pushups in lakes affected by seismic exploration are equivocal. Additional surveys would be desirable to obtain the sample sizes necessary for confidently assessing degree of impact.

The major area in which data are lacking pertains to the behavioral responses of muskrats to seismic disturbance. Neither the approach nor the equipment employed in 1976 were adequate for obtaining this type of information. It appears that this data could best be obtained through detailed telemetry monitoring of activity of individual muskrats.

It should be apparent that the above mentioned studies would require a very large commitment on the part of the exploration company involved. If additional studies of this type are contemplated, negotiations between all participating agencies should begin well in advance of the intended starting date.

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PHOTOGRAPHS



Photo 1. Lakes in the Study Area generally are small and shallow. *Picea glauca* is the dominant tree species.



Photo 2. Shoreline vegetation primarily comprises *Alnus*, *Salix* and grasses. Banks are typically steep, the result of thermokarst action.



Photo 3. Instruments used to measure pressure changes in water (hydrophones).



Photo 4. Muskrats were placed in a simulated bank-burrow to test pathological effects of seismic blasting.

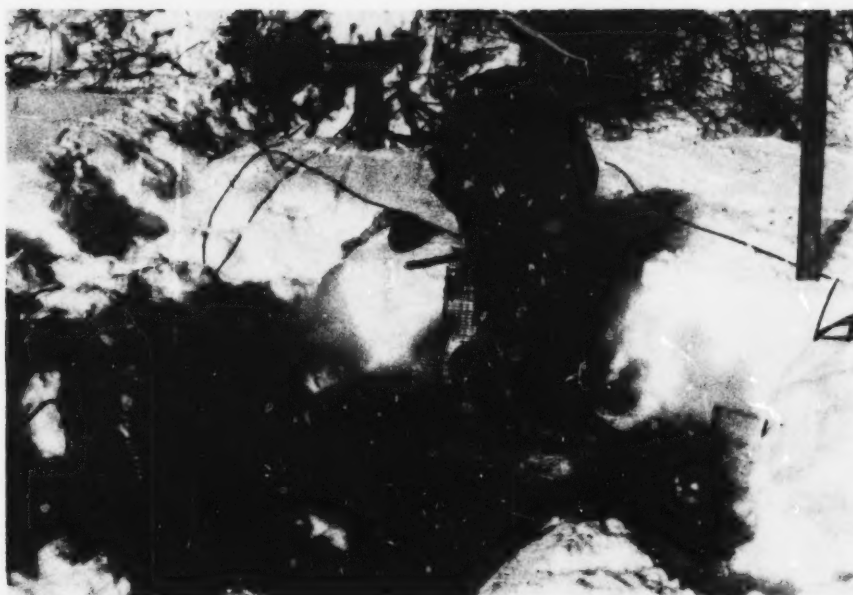


Photo 5. Animals were lowered into water one meter below ice surface during experimental blasts. They remained submerged for 45 seconds.



Photo 6. Live-traps set at pushups were insulated with styrofoam and covered with a thick layer of loose snow.



Photo 7. A heated wooden box was used to ameliorate the muskrat's immediate environment during tagging procedures.

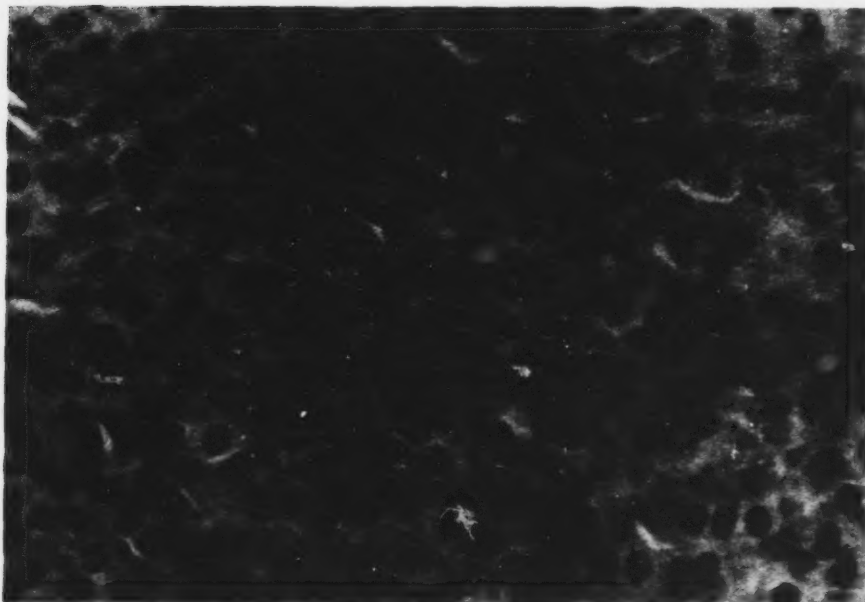


Photo 8. Histological section of adrenal gland of unstressed animal (120X).

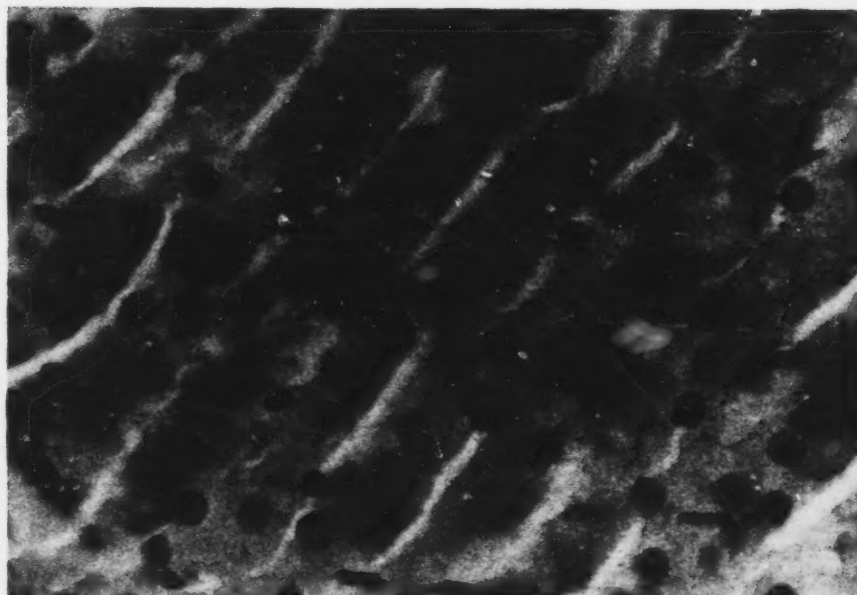


Photo 9. Histological section of adrenal gland of stressed muskrat (120X). Cellular hypertrophy within the zona fasciculata is evident.

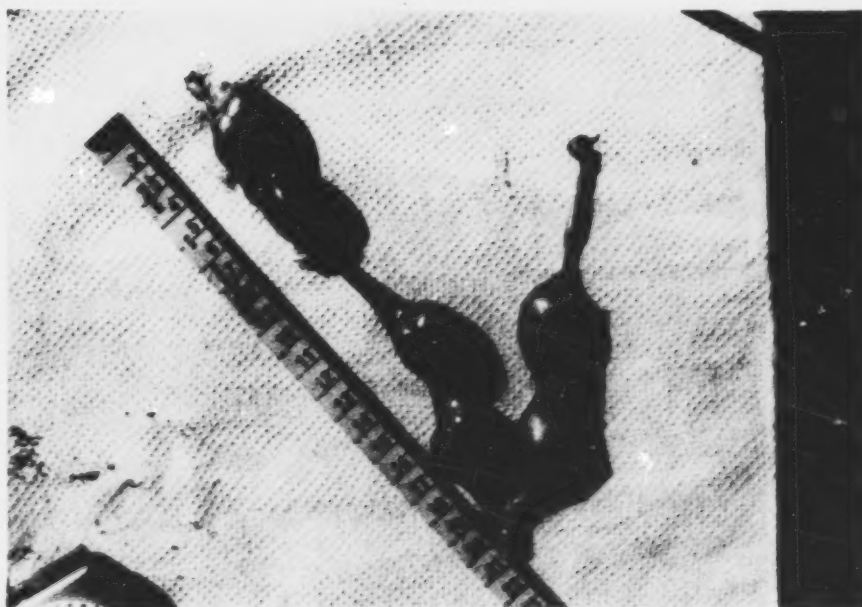


Photo 10. Muskrat uterus with two resorbed embryos. Resorptions were found in 26% of all gravid females.



Photo 11. Active bank-burrow located at point where seismic line crossed lakeshore.



Photo 12. Ground cover and shrubbery are virtually unimpaired on old seismic line re-used two months before this photo.

Appendix I. Comparative summary of Inuvik meteorological information.

	1974	1975	1976	Adjusted Mean 1941 - 1970
Mean Daily Temperature (°C)				
March	-26.8	-20.7	-26.0	-23.8
April	-18.2	-13.6	-8.4	-14.5
May	-0.6	0.0	1.1	-0.8
June	7.1	10.6	8.9	9.8
Mean Daily Maximum Temperature (°C)				
March	-20.5	-14.6	-19.6	-17.7
April	-11.6	-7.1	-2.1	-7.9
May	5.4	4.5	6.2	3.9
June	13.1	16.7	14.9	16.0
Mean Daily Minimum Temperature (°C)				
March	-32.9	-26.7	-32.3	-30.0
April	-24.8	-20.2	-14.6	-21.2
May	-6.5	-4.6	-4.0	-5.7
June	1.1	4.5	2.8	3.7
Mean Total Precipitation (mm)				
March	0.5	6.9	11.3	16.5
April	2.5	21.8	1.2	14.0
May	2.5	8.4	61.6	17.5
June	18.3	21.1	29.2	12.0
Mean Snowfall (cm)				
March	0.8	11.4	12.4	18.5
April	4.1	23.6	2.7	15.0
May	2.8	7.6	21.6	14.0
June	7.6	Trace	3.0	2.3
Snow Depth (cm)				
January 31	25	58	51	
February 28	28	61	53	
March 31	28	71	56	
April 30	28	61	23	

APPENDIX II. Calculation of population size on four study lakes.

The following population estimates have been calculated using the Schnabel Method (Chapman and Overton 1966). Modification of the method to account for removal of marked and unmarked individuals (Overton 1965) has not been attempted at this time.

In calculating the pre-seismic(*) and post-seismic(**) estimators, we let

$X_i = \Sigma X_i$ = cumulative total of marked animals captured

$\lambda = \Sigma n_i M_i$

where

X_i = number of marked animals captured at the i th period

n_i = total number captured at the i th period

M_i = number of marked animals in the population at the i th period

then

$$\hat{N} = \frac{\lambda}{X_i + 1} = \text{population estimate at the } i\text{th period}$$

assuming marked and unmarked animals are equally likely to be captured.

Table 11. Calculation of population levels on Lakes E and E₁ by the Schnabel Method.

Trapping Period	n_i	m_i	M_i	$n_i M_i$	$\Sigma n_i M_i = \lambda$	x_i	X_i	$\frac{\lambda}{X_i + 1} = \hat{N}$
<u>LAKE E</u>								
<u>Pre-seismic</u>								
1	2	2	0	0				
2	3	3	2	6	6	0	0	
3	5	5	5	25	31	0	0	
4	7	6	10	70	101	1	1	51
5	7	5	16	112	213	2	3	53
6	4	2	21	84	297	2	5	50
7	3	2	23	69	366	1	6	52
8	6	1	25	150	516	2	8	57
9	5	2	26	130	646	3	11	54*
<u>Post-seismic</u>								
10	9		28	252	898	6	17	50
11	6		22	132	1030	2	19	52
12	8		20	160	1190	2	21	54
13	9		16	144	1334	4	25	51
14	3		12	36	1370	1	26	51
15	4		11	44	1414	1	27	51**
<u>LAKE E₁</u>								
<u>Pre-seismic</u>								
1	3	3	0					
2	3	2	3	9	9	0		
3	4	4	5	20	29	0		
4	5	4	9	45	74	1	1	37
5	5	4	13	65	139	1	2	46
6	4	2	17	68	207	2	4	41
7	5	2	19	95	302	3	7	38
8	5	0	21	105	407	4	11	34
9	3	1	21	63	470	2	13	34*
<u>Post-seismic</u>								
10	4		22	88	558	4	17	31
11	2		18	36	594	2	19	30
12	3		16	48	642	2	21	29
13	4		14	56	698	1	22	30
14	1		13	13	711	1	23	30
15	1		12	12	723	1	24	29**

Table 12. Calculation of population levels on Lakes F and F₁ by the Schnabel Method.

Trapping Period	n_i	m_i	M_i	$n_i M_i$	$\Sigma n_i M_i = \lambda$	x_i	X_i	$\frac{\lambda}{X_i + 1} = \hat{N}$
<u>LAKE F</u>								
<u>Pre-seismic</u>								
1	3	3						
2	7	7	3	21		0		
3	6	4	10	60	81	2	2	27
4	6	3	14	84	165	3	5	28
5	6	1	17	102	267	5	10	24
6	6	3	18	108	375	3	13	27*
<u>Post-seismic</u>								
7	8		21	168	543	2	15	34
8	4		19	76	619	0	15	39
9	3		19	57	676	1	18	36
10	3		18	54	730	2	20	35
11	4		16	64	794	4	24	32
12	3		12	36	830	2	26	31
13	2		10	20	850	1	27	30**
<u>LAKE F₁</u>								
<u>Pre-seismic</u>								
1	3	1						
2	3	3	1	3		0		
3	4	4	4	16	19	0		
4	3	3	8	24	43	0		
5	0	0	11	0	43	0		
6	3	2	11	33	76	1	1	38*
<u>Post-seismic</u>								
7	3		13	39	115	2	3	29
8	6		11	66	181	3	6	26
9	2		8	16	197	1	7	25
10	3		7	21	218	0	7	27
11	5		7	35	253	3	10	23
12	3		4	12	265	1	11	22
13	2		3	6	271	0	11	23**

Confidence limits (95%) were determined under the assumption that X_i has approximately a Poisson distribution with mean λ/N , thus

$$P \left[\underline{X} \leq \frac{N}{\lambda} \leq \bar{X} \right] = 1 - \alpha$$

where $\underline{X}$ and $\bar{X}$ are the lower and upper confidence limits.

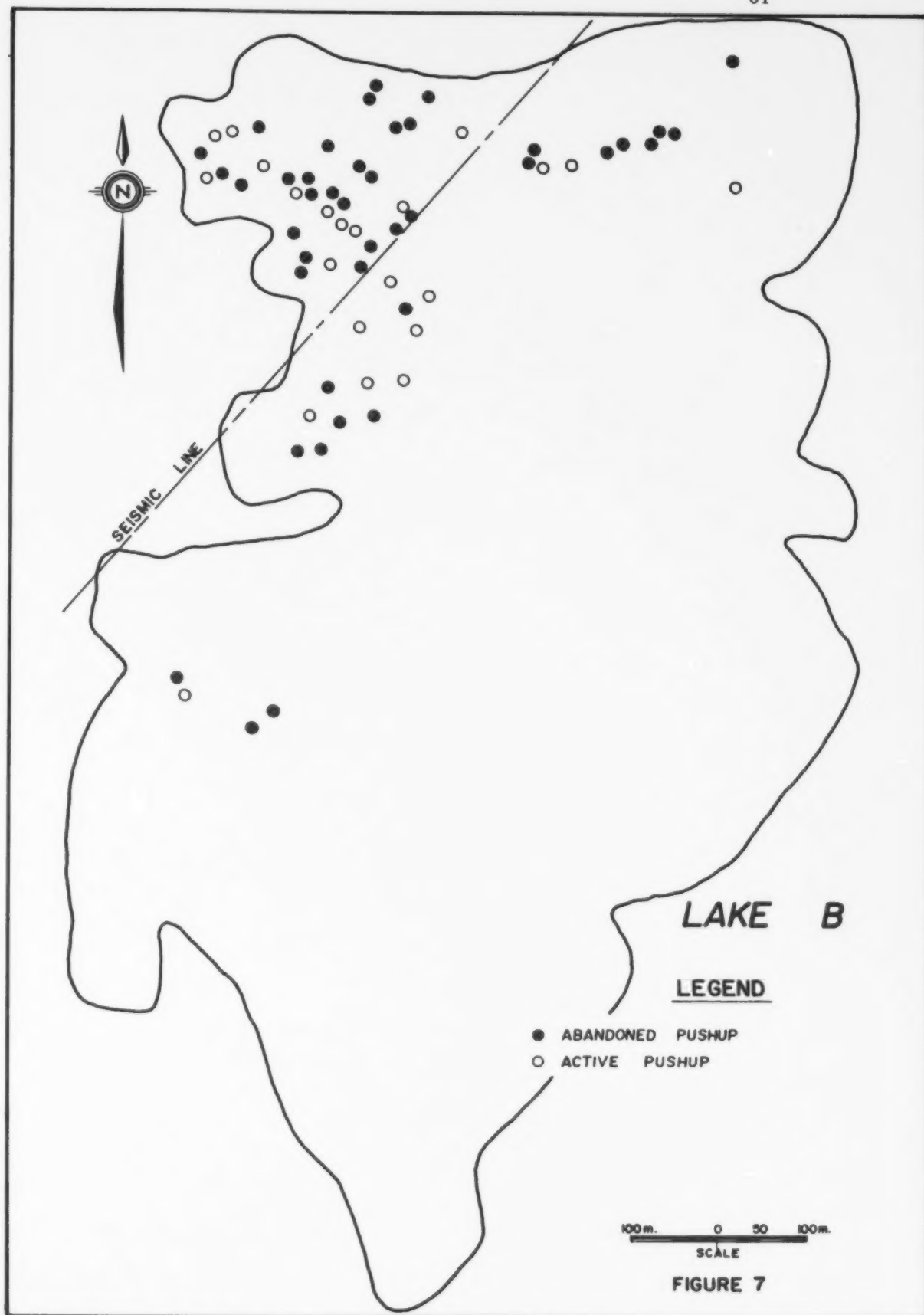
So, confidence limits for estimates obtained in this study are:

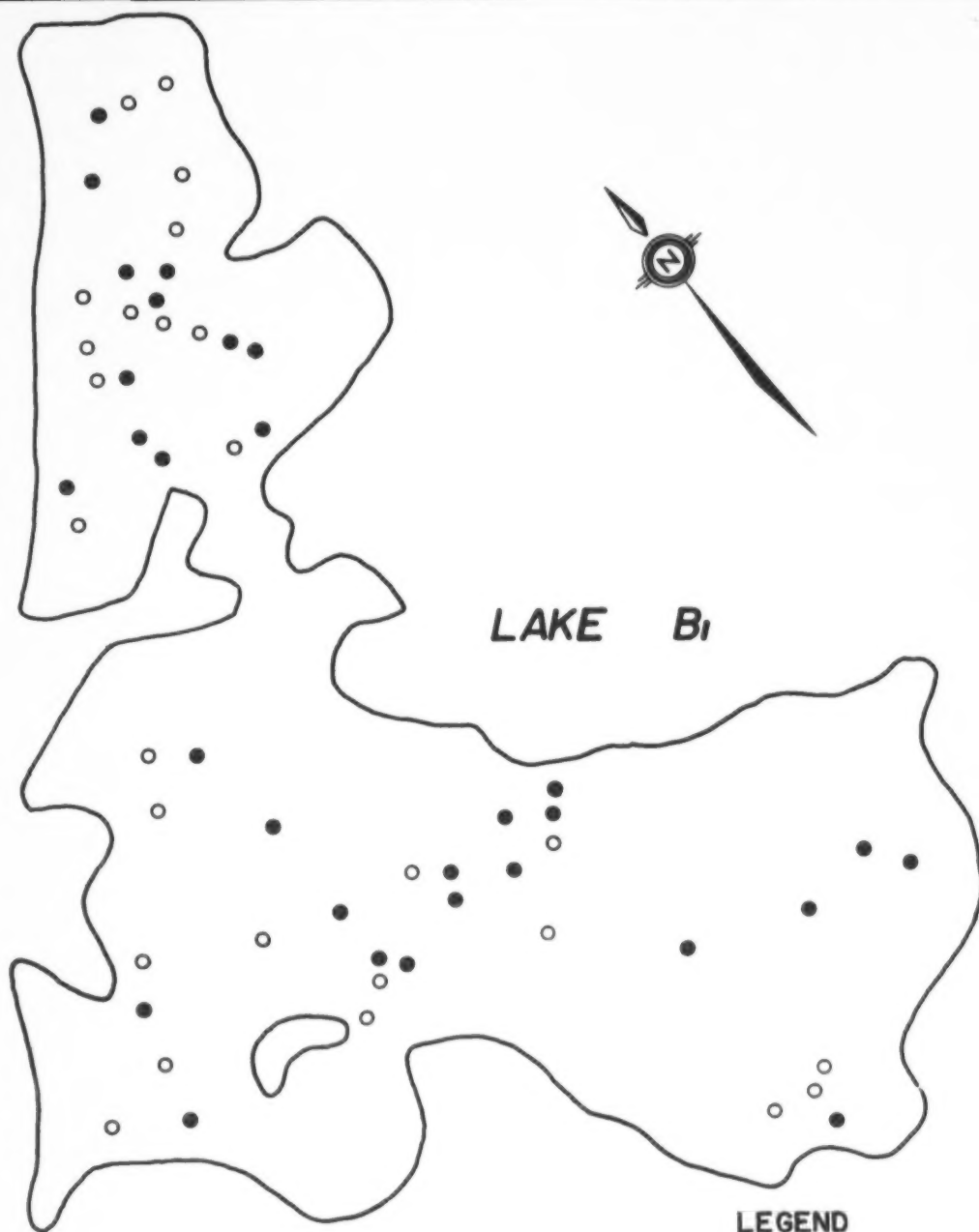
Lake E	pre-seismic $\hat{N} = 54$
	$(646)(.0443) \leq N \leq (646)(.165)$
	$28.62 \leq N \leq 106.59$
	post-seismic $\hat{N} = 51$
	$(1414)(.02408) \leq N \leq (1414)(.0539)$
	$34.05 \leq N \leq 76.21$
Lake E ₁	pre-seismic $\hat{N} = 34$
	$(470)(.0400) \leq N \leq (470)(.133)$
	$18.80 \leq N \leq 62.51$
	post-seismic $\hat{N} = 29$
	$(723)(.02632) \leq N \leq (723)(.0620)$
	$19.03 \leq N \leq 44.83$
Lake F	pre-seismic $\hat{N} = 27$
	$(375)(.0400) \leq N \leq (375)(.133)$
	$15.00 \leq N \leq 49.88$
	post-seismic $\hat{N} = 30$
	$(850)(.02408) \leq N \leq (850)(.0539)$
	$20.47 \leq N \leq 45.82$
Lake F ₁	pre-seismic $\hat{N} = 38$
	$(76)(.0720) \leq N \leq (76)(19.489)$
	$5.47 \leq N \leq 1481.16$
	post-seismic $\hat{N} = 23$
	$(271)(.0443) \leq N \leq (271)(.165)$
	$12.01 \leq N \leq 44.72$

Confidence limits taken from Chapman (1948).

APPENDIX III

MAPS OF STUDY LAKES



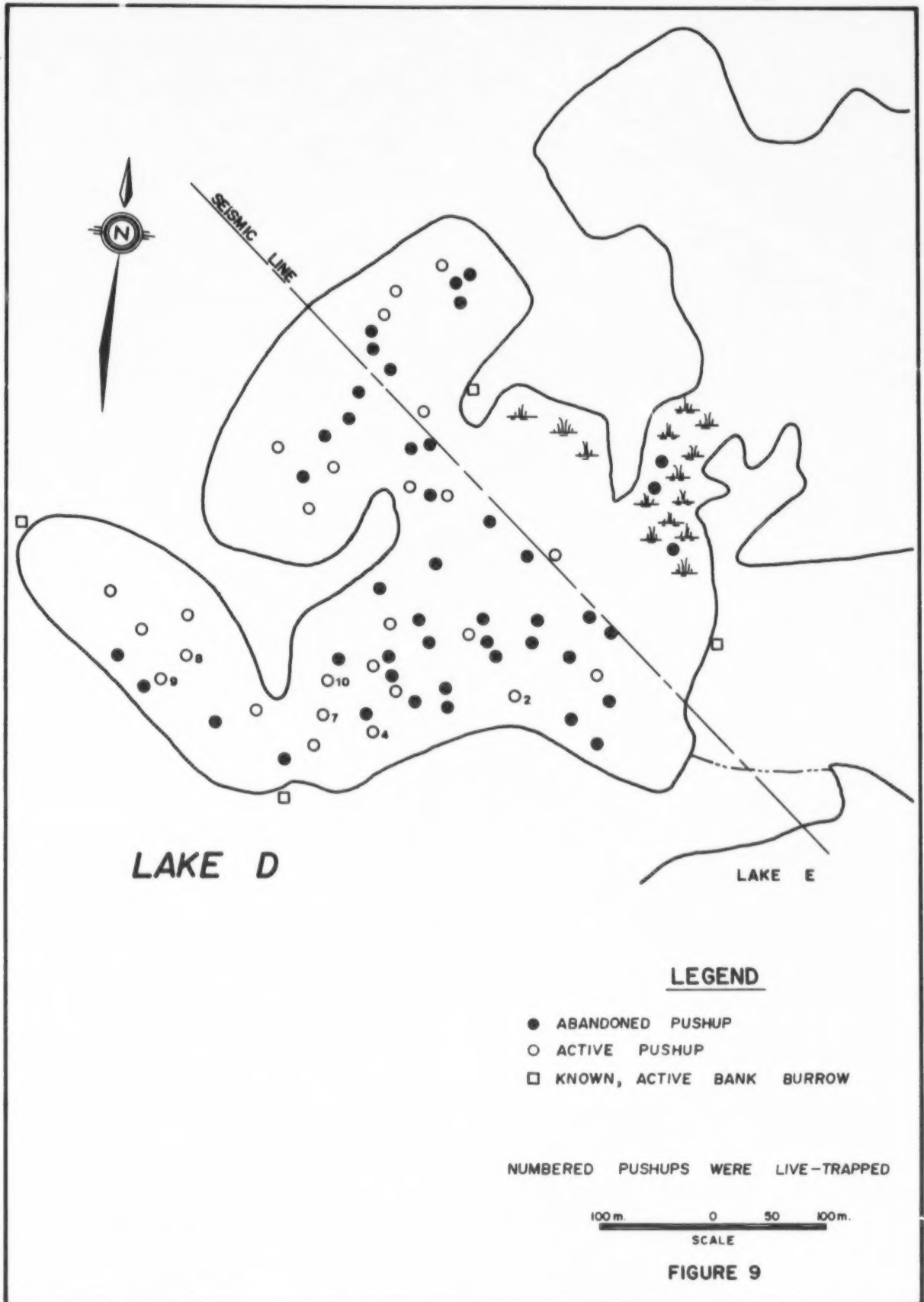


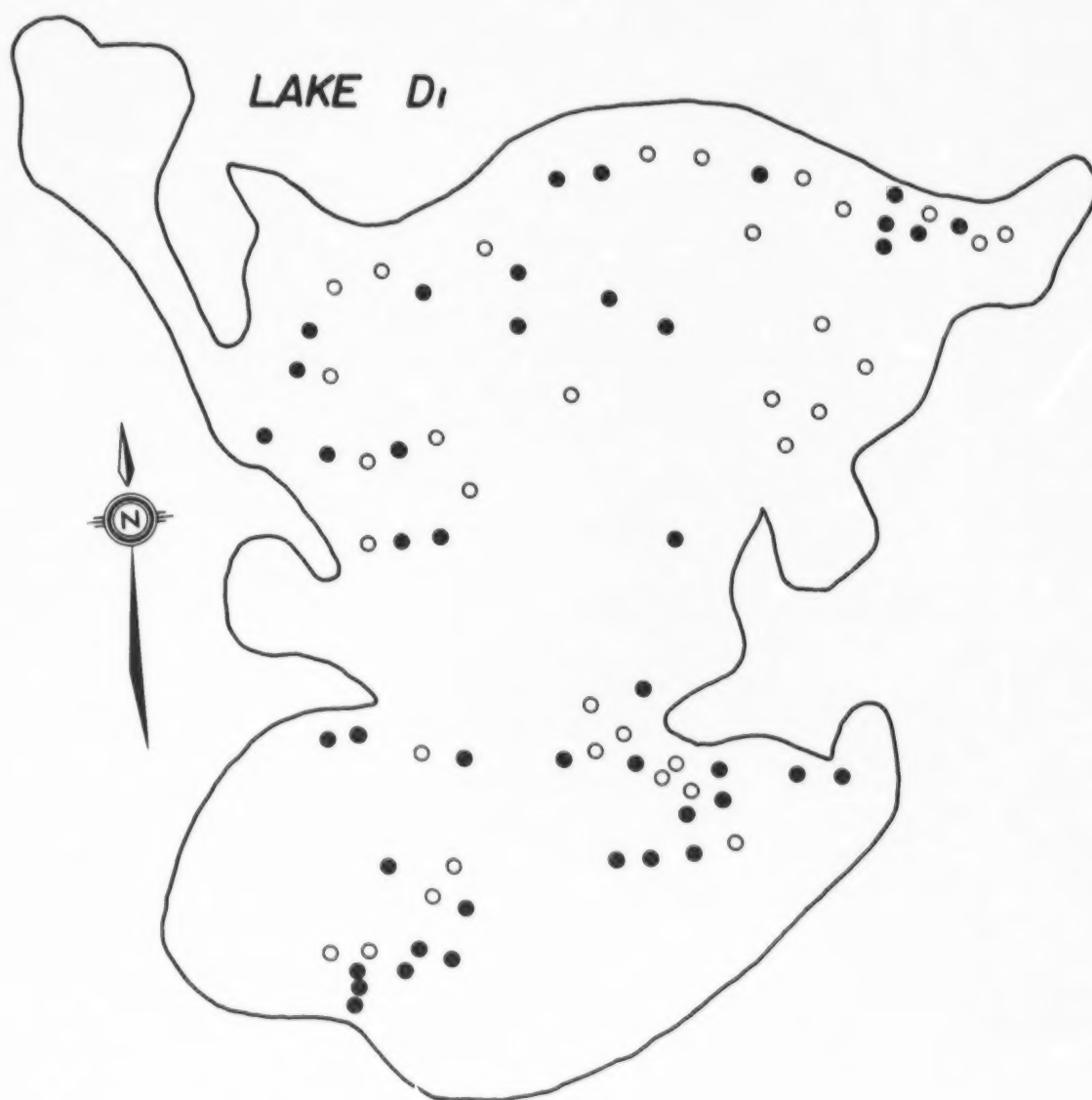
LEGEND

- ABANDONED PUSHUP
- ACTIVE PUSHUP

100m. 0 50 100m.
SCALE

FIGURE 8



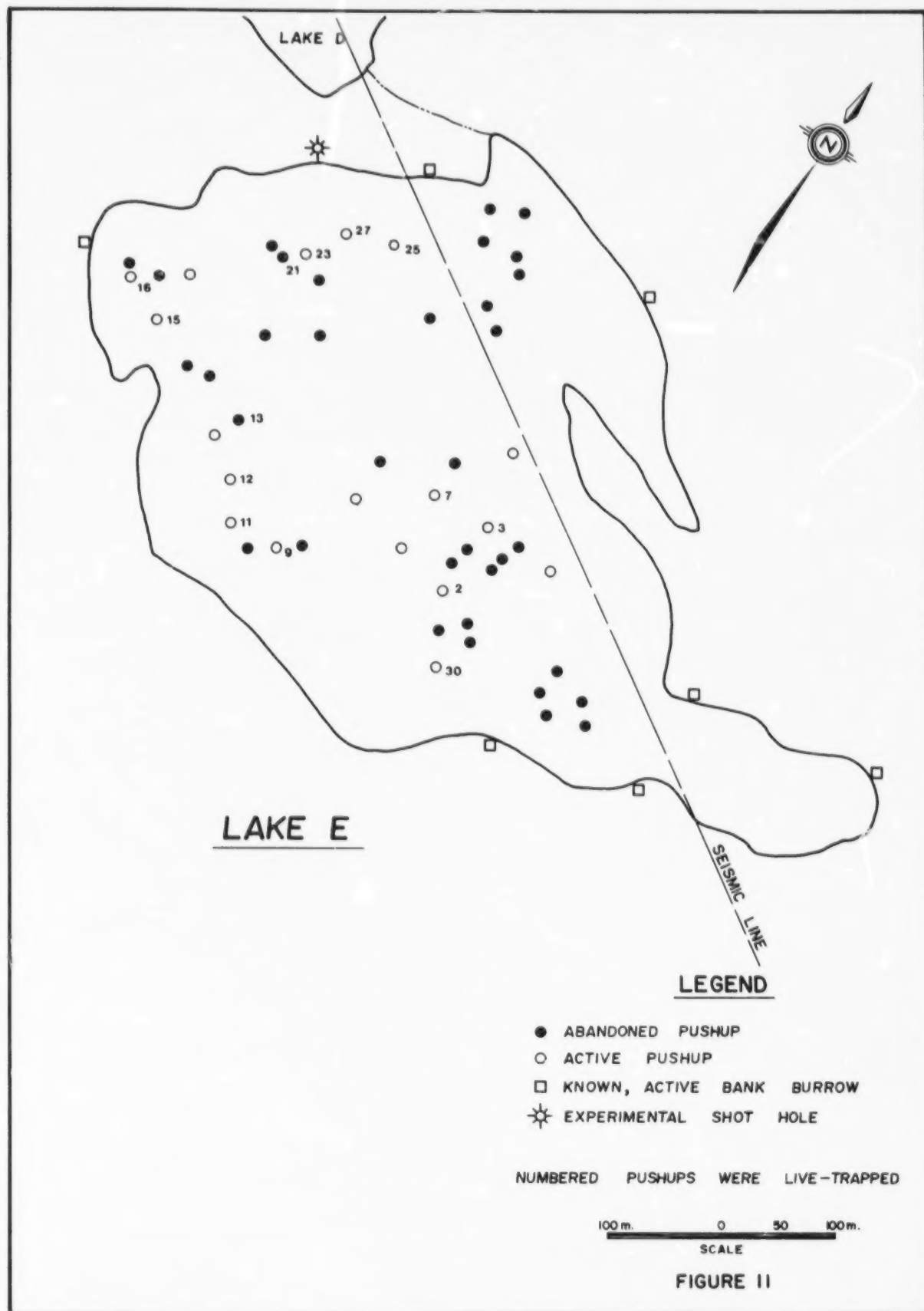


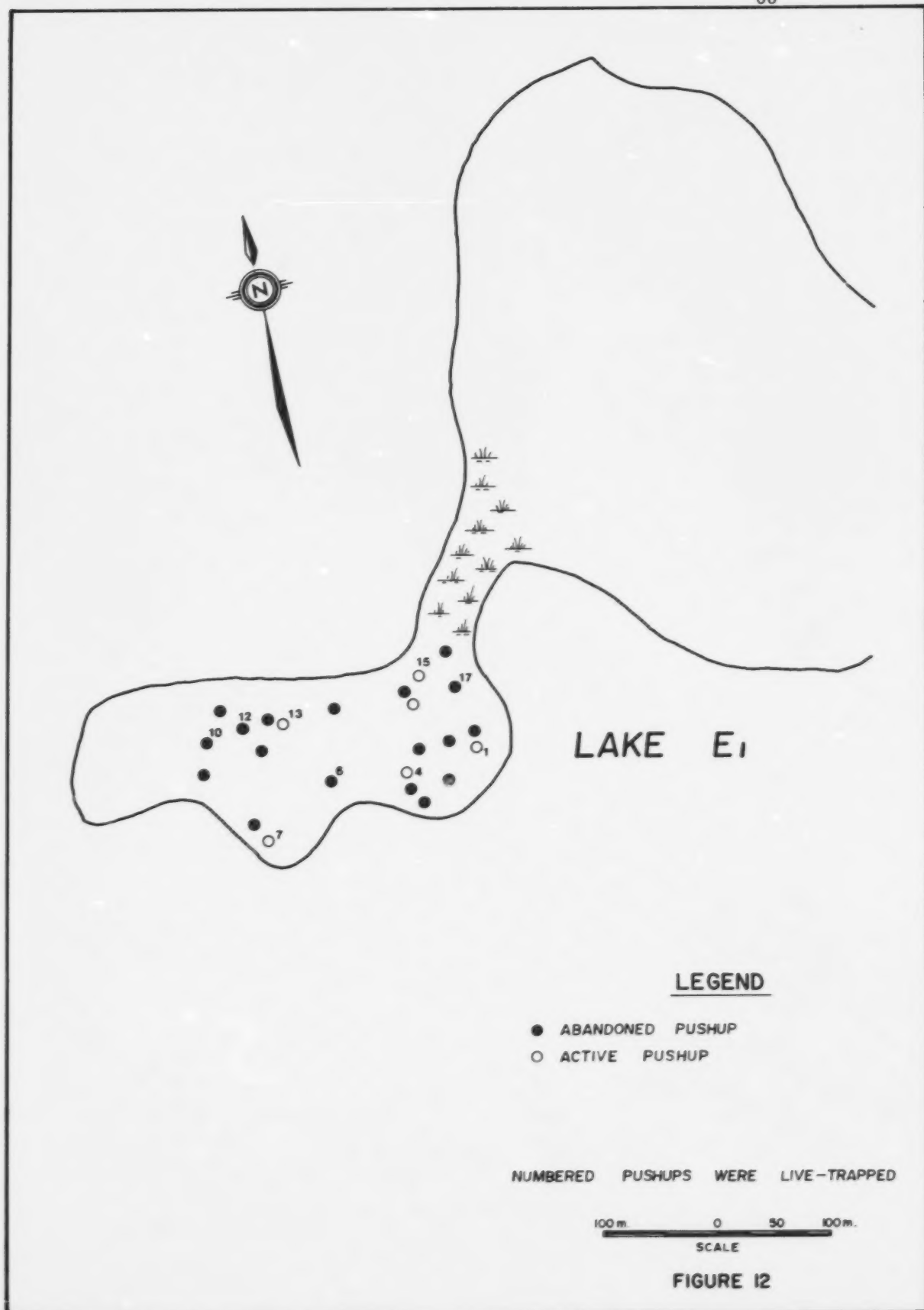
LEGEND

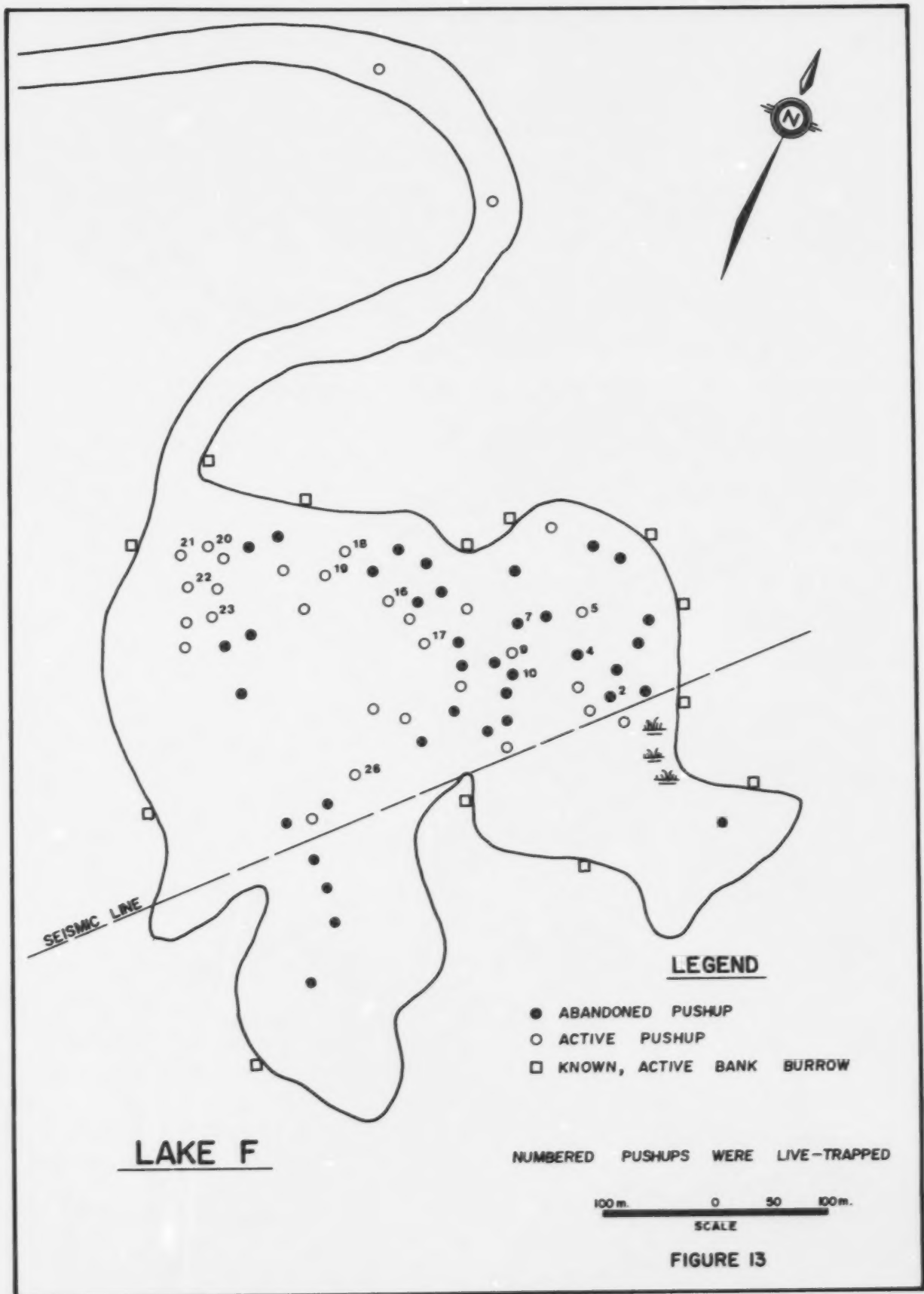
- ABANDONED PUSHUP
- ACTIVE PUSHUP

100m. 0 50 100m.
SCALE

FIGURE 10







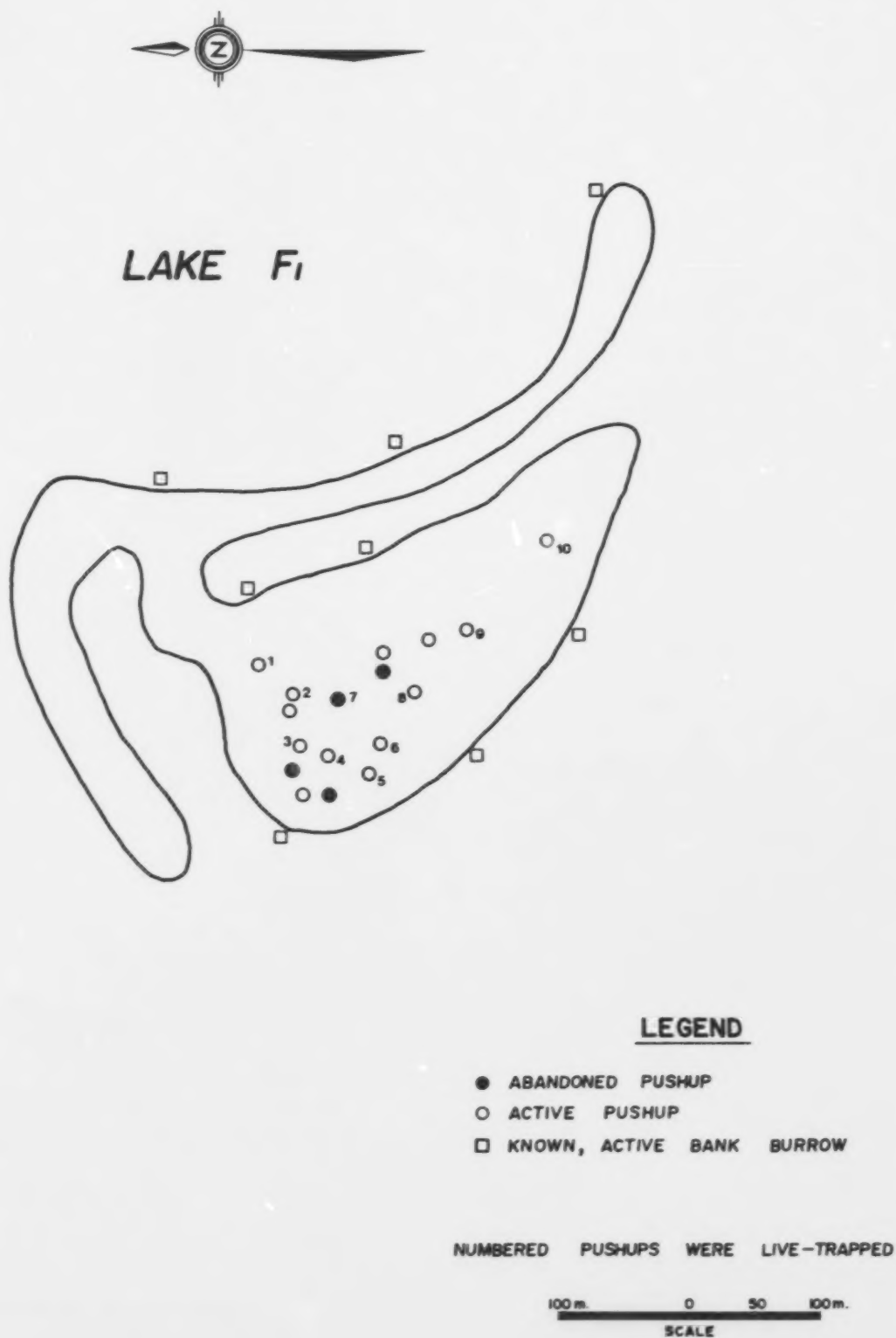


FIGURE 14

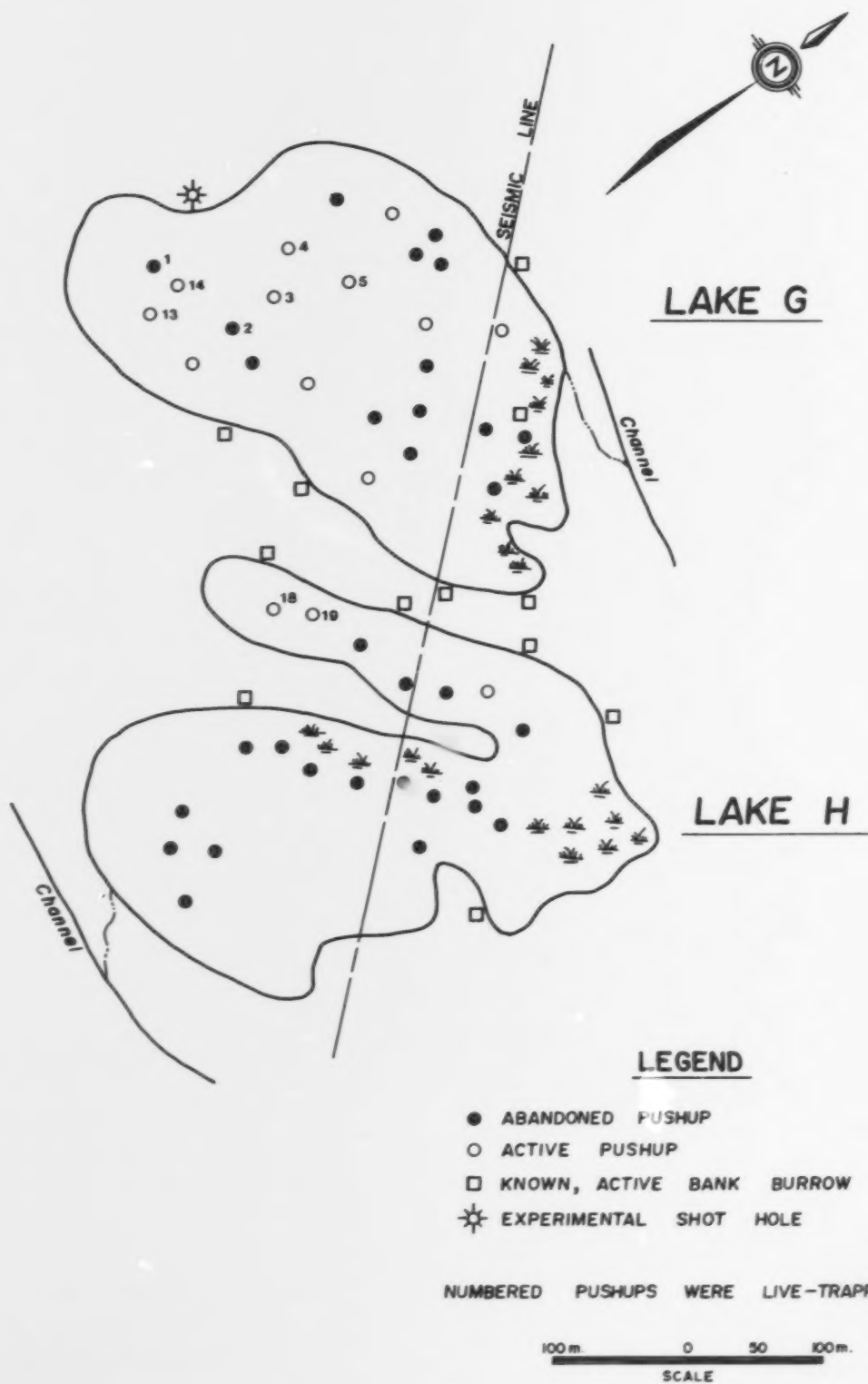


FIGURE 15

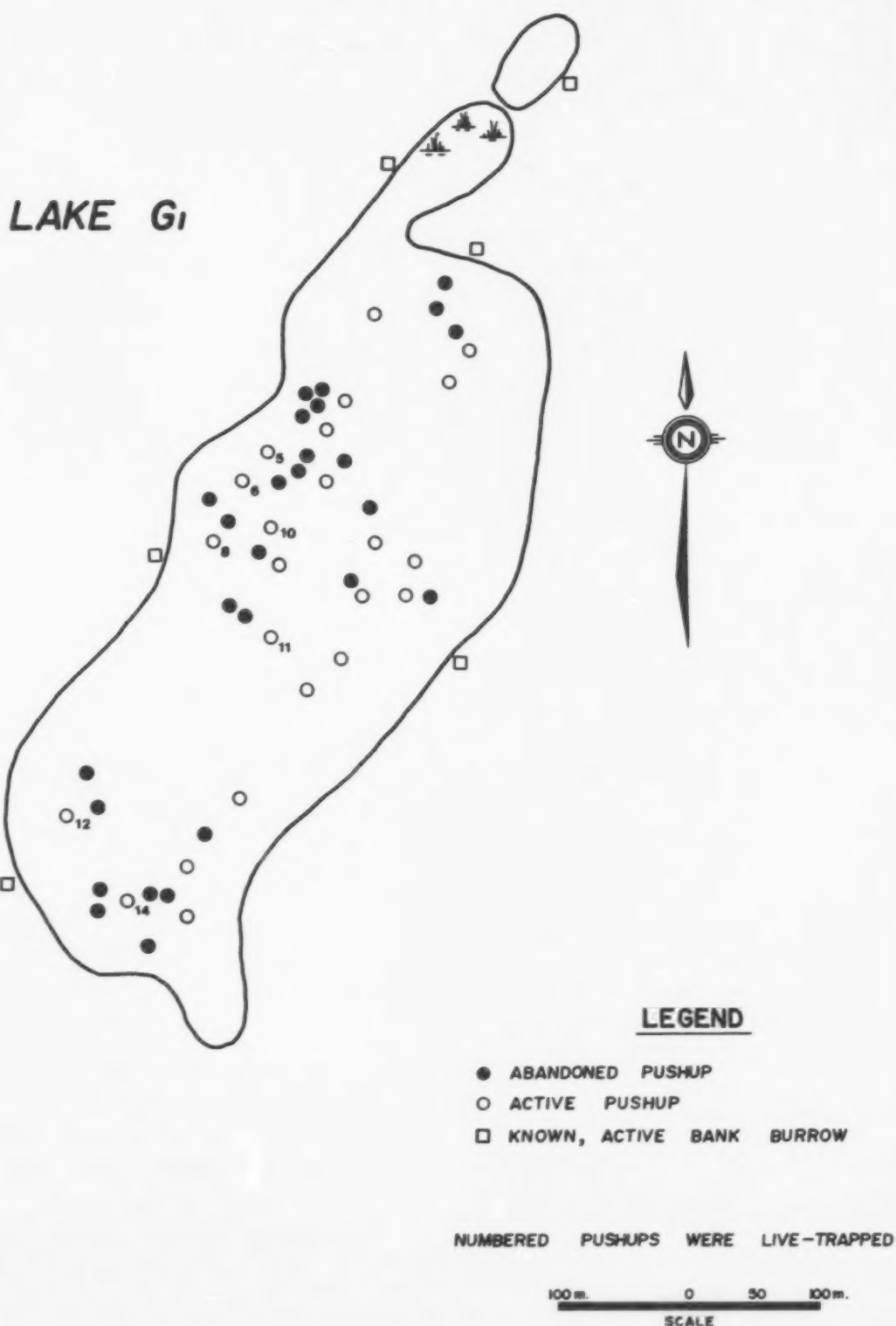


FIGURE 16

